Updates to the Low Energy Excess in MiniBooNE

Chris Polly, Indiana University*

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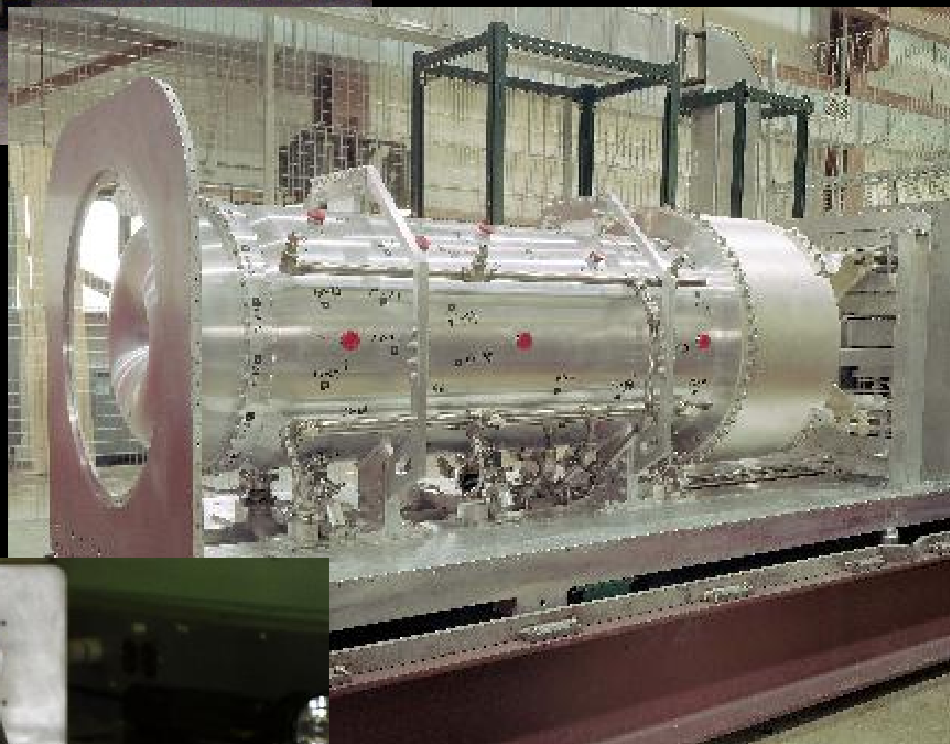

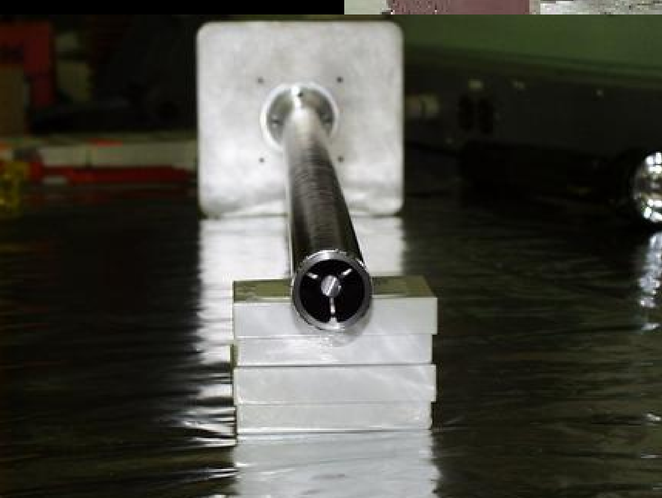

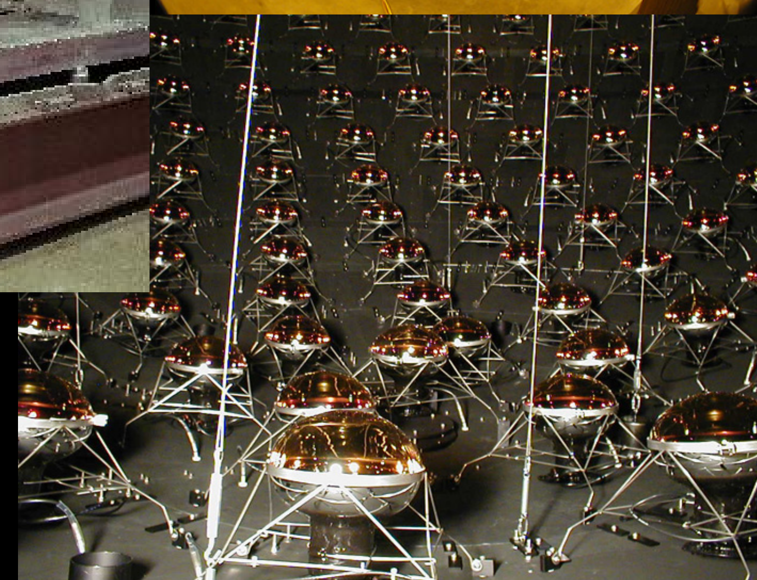

The MiniBooNE Collaboration

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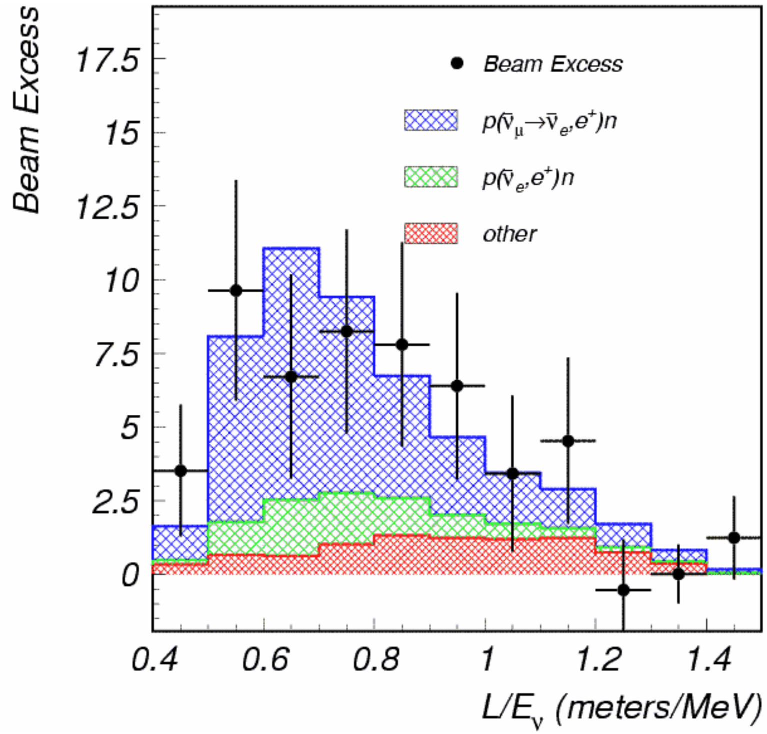
~80 physicists from ~18 institutions

OUTLINE

- Recap of last year's neutrino oscillation result
- Analysis updates, emphasis on ν_e–like excess at low energy
- Status of antineutrino running

MiniBooNE's Motivation: The LSND signal



- LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a 2ν mixing hypothesis:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

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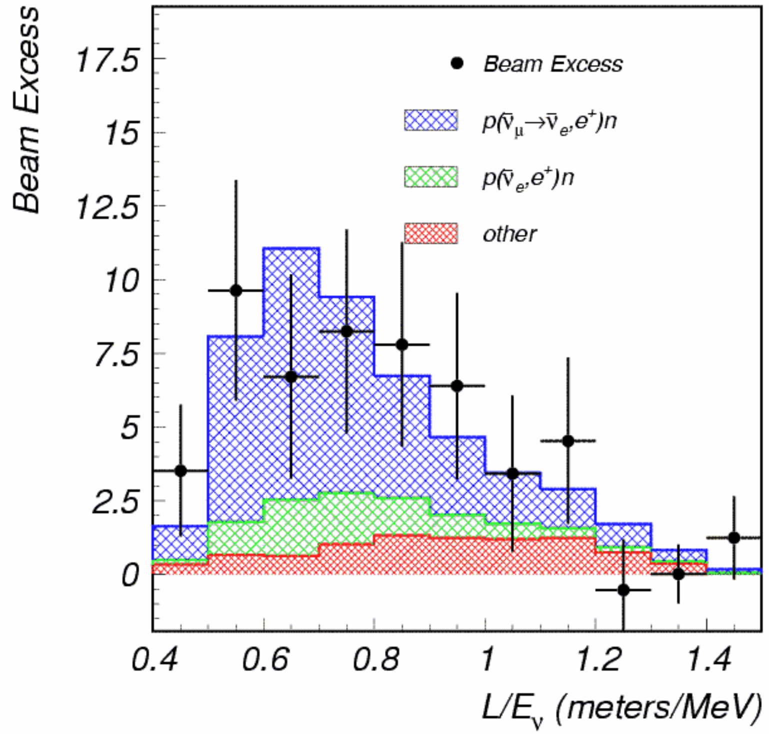

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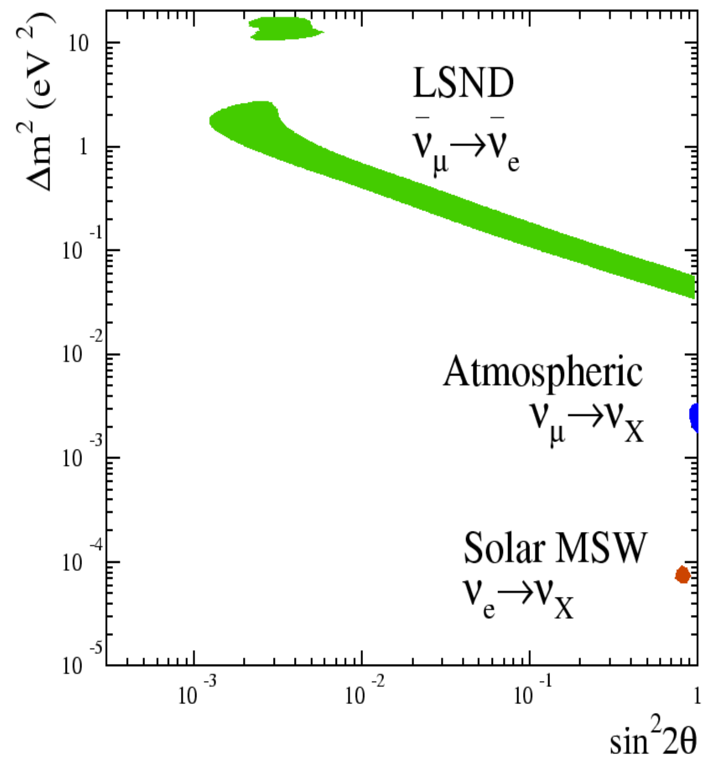
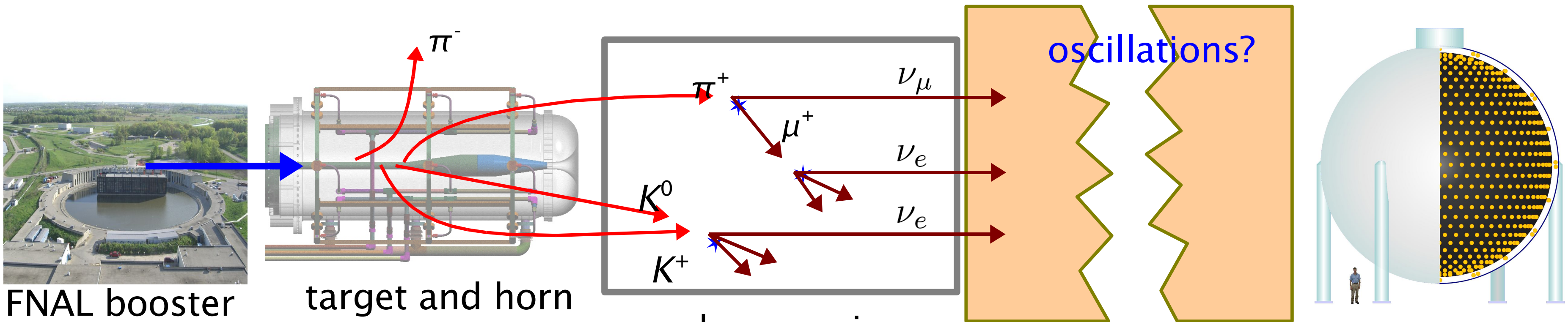


- $\Delta m^2 \sim 1$ eV^2 impossible with only 3ν
- Requires extraordinary physics!
  - Sterile neutrinos *hep-ph/0305255*
  - Neutrino decay *hep-ph/0602083*
  - Lorentz/CPT viol. *PRD(2006)105009* (T. Katori, A. Kostelecky, R. Tayloe)
  - Extra dimensions *hep-ph/0504096*
- Unlike atmos and solar...LSND unconfirmed

The MiniBooNE design strategy...must make ν_μ



FNAL booster (8 GeV protons)

target and horn (174 kA)

decay region (50 m)

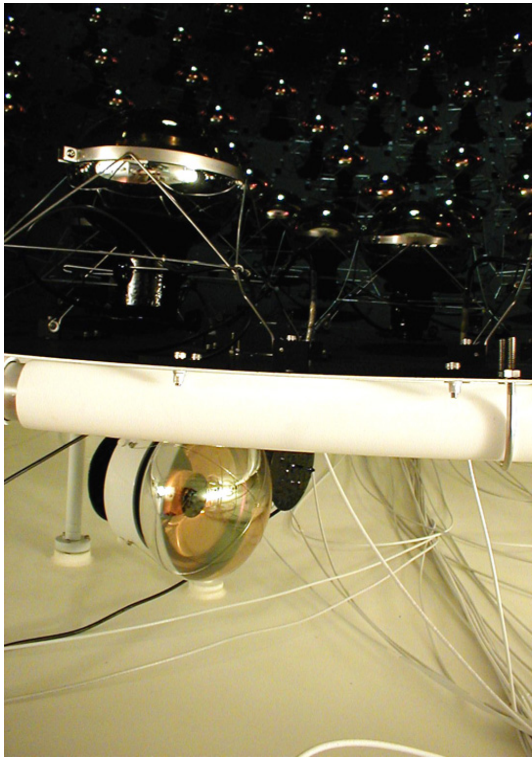
dirt (~500 m)

detector

- Start with 8 GeV proton beam from FNAL Booster
- Add a 174 kA pulsed horn to gain a needed x 6
- Requires running ν (not anti-ν) to get flux
- Pions decay to ν with E_ν in the 0.8 GeV range
- Place detector to preserve LSND L/E:

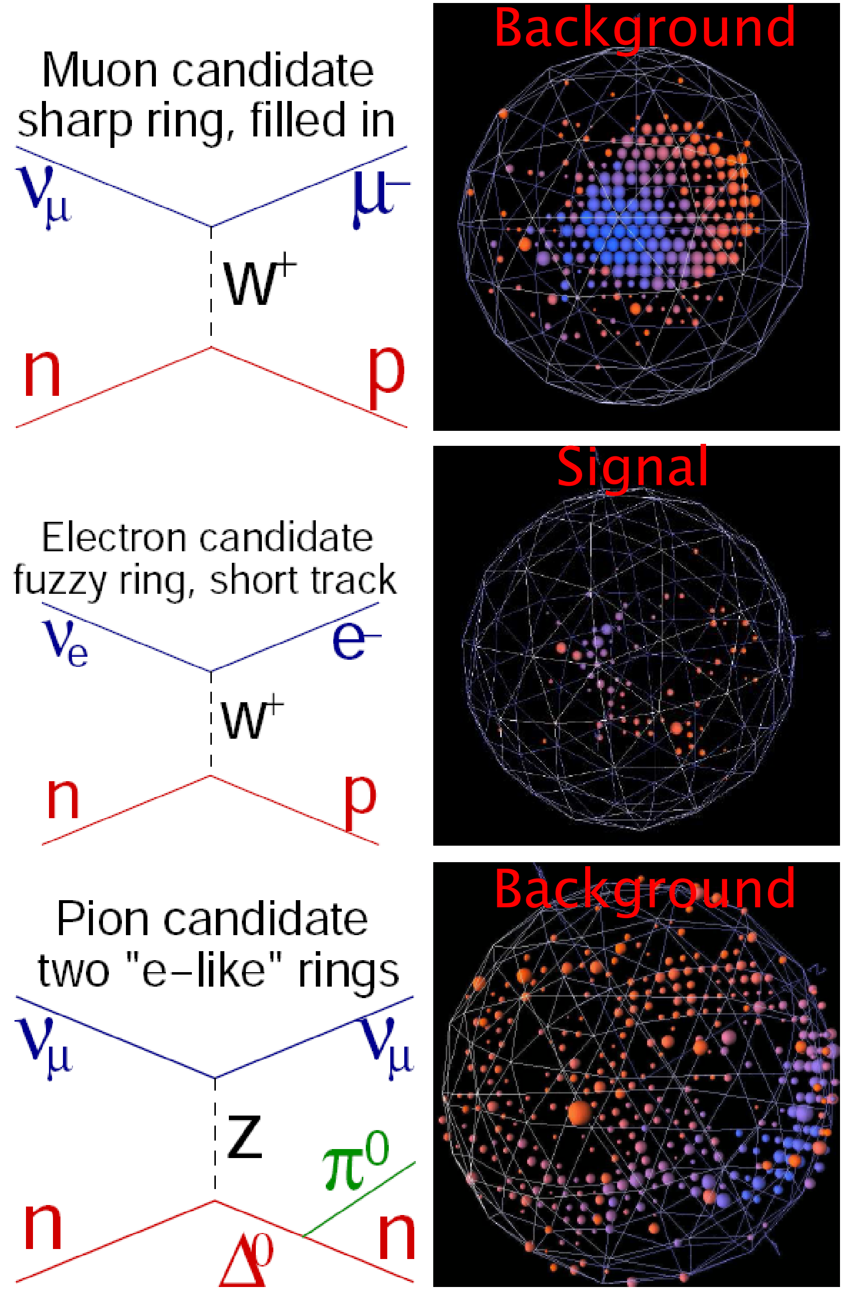
MiniBooNE:	(0.5 km) / (0.8 GeV)
LSND:	(0.03 km) / (0.05 GeV)

- Detect ν interactions in 800T pure mineral oil detector
  - 1280 8” PMTs provide 10% coverage of fiducial volume
  - 240 8” PMTs provide active veto in outer radial shell

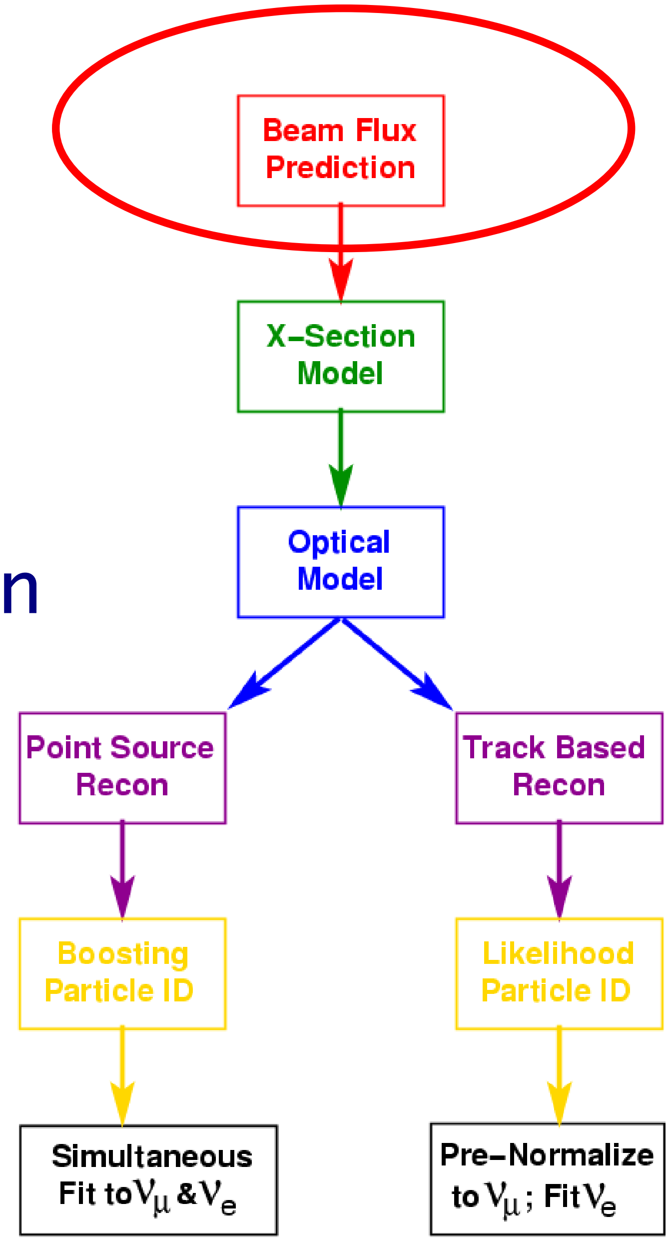


Key points about the signal

- LSND oscillation probability is < 0.3%
- After cuts, MiniBooNE has to be able to find ~300 ν_e CCQE interactions in a sea of ~150,000 ν_μ CCQE
- Intrinsic ν_e background
  - Actual ν_e produced in the beamline from muons and kaons
  - Irreducible at the event level
  - E spectrum differs from signal
- Mis-identified events
  - ν_μ CCQE easy to identify, i.e. 2 “subevents” instead of 1. However, lots of them.
  - Neutral-current (NC) π^0 and radiative Δ are more rare, but harder to separate
  - Can be reduced with better PID
- Effectively, MiniBooNE is a ratio meas. with the ν_μ constraining flux X cross-section

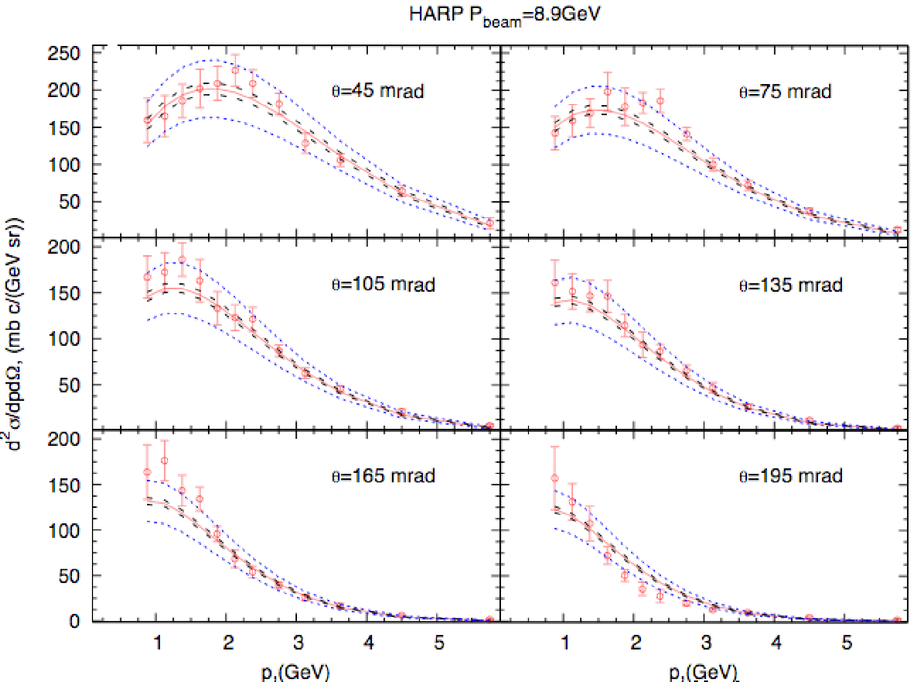


Analysis Chain: Flux Prediction



Meson production at the target

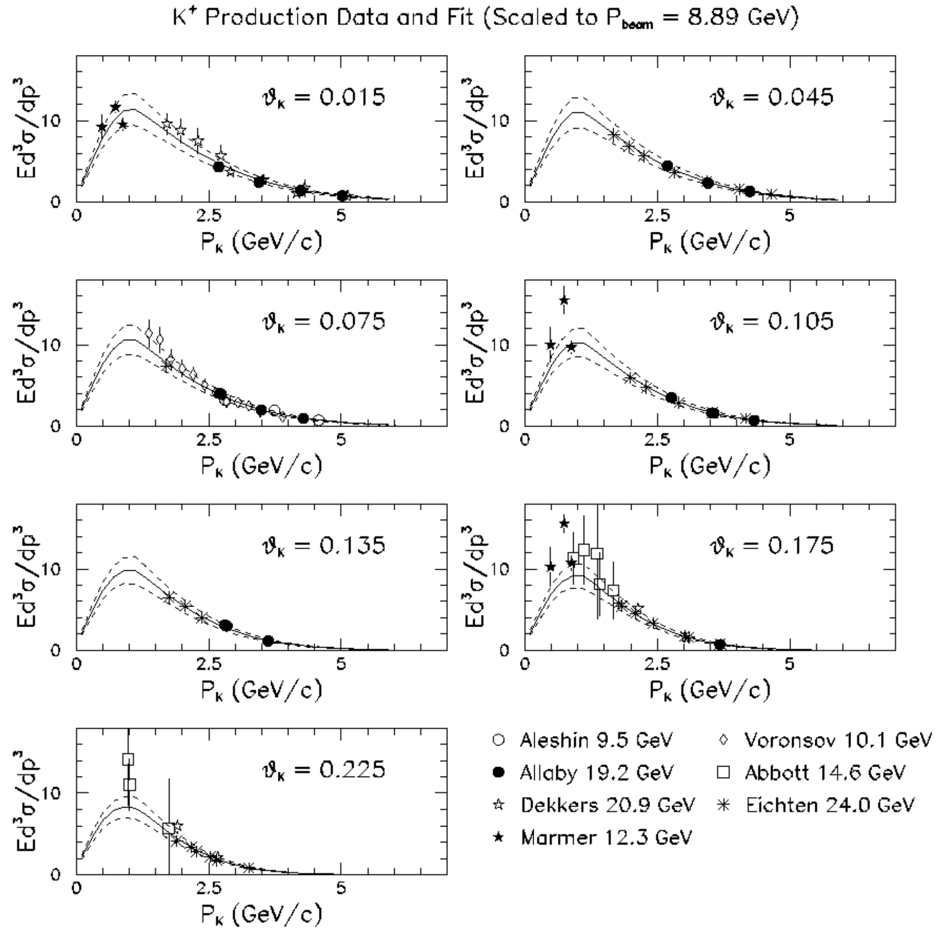
Pions:



HARP collaboration, hep-ex/0702024

- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% λ Beryllium target
- Data were fit to Sanford-Wang parameterization

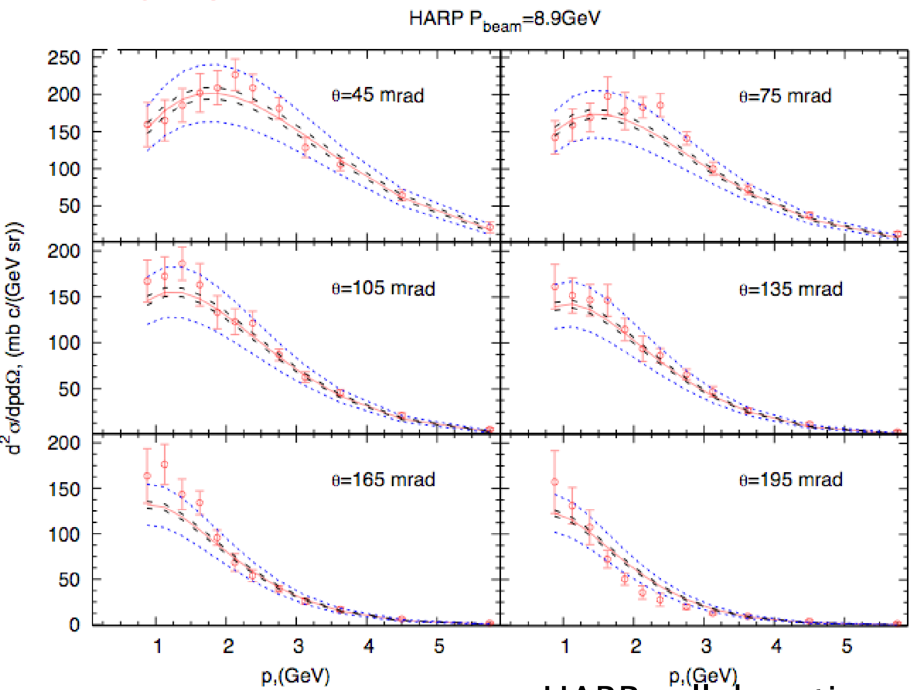
Kaons:



- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

Meson production at the target

Pions:



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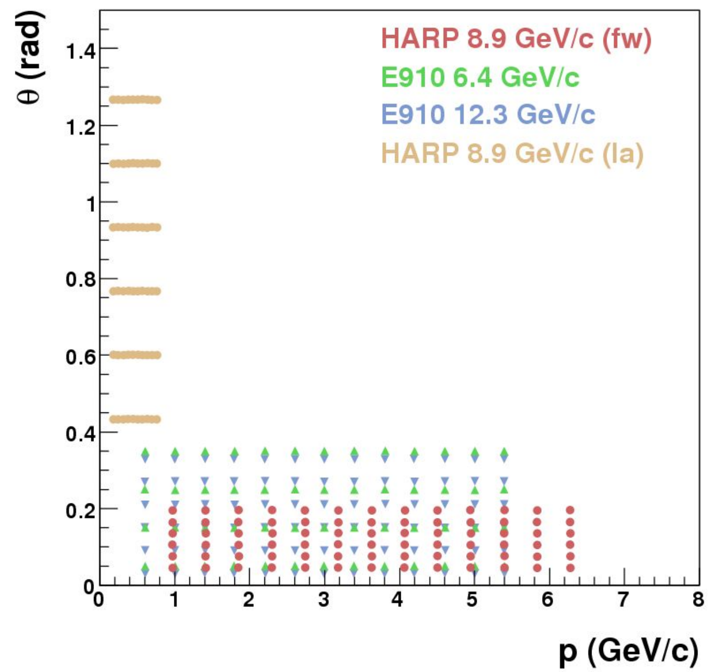
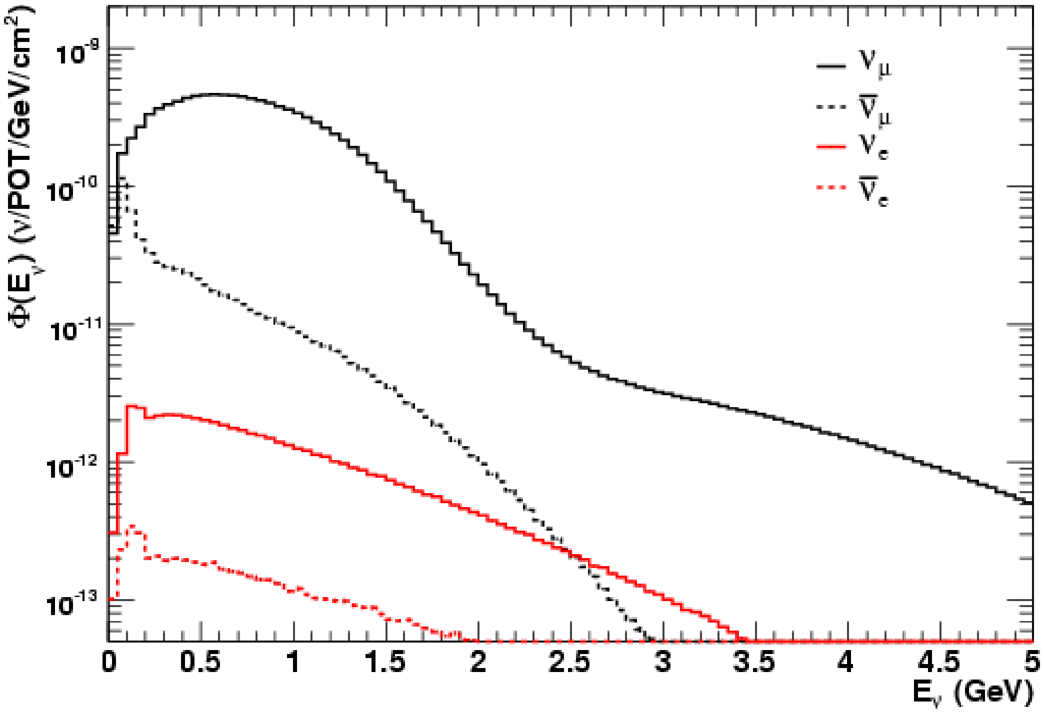
Aside on relevance to Project X:

- MiniBooNE flux carefully tuned and verified with ν beam $\Rightarrow$ most robust MC available for predicting π and K fluxes at Booster energies.
- Muon g-2 example: MB provided flux prediction for very forward (θ<45mrad) 3 GeV pions.

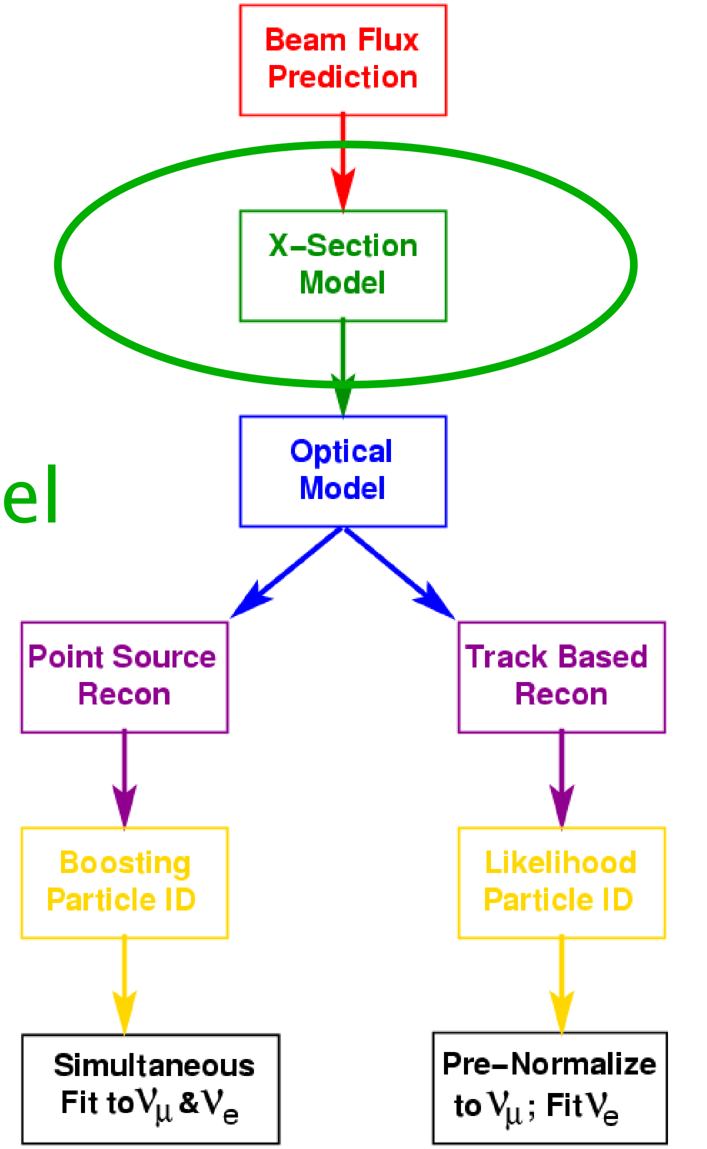


Final neutrino flux estimation



- Flux intersecting MB detector (not cross-section weighted)
- Intrinsic contamination ν_e / ν_μ = 0.5%
  - $\mu^+ \to e^+ \, \bar{\nu}_\mu \, \nu_e$ (52%)
  - $K^+ \to \pi^0 \, e^+ \, \nu_e$ (29%)
  - $K^0 \to \pi \, e \, \nu_e$ (14%)
  - Other (5%)
- Wrong-sign $\bar{\nu}_\mu$ content: 6%

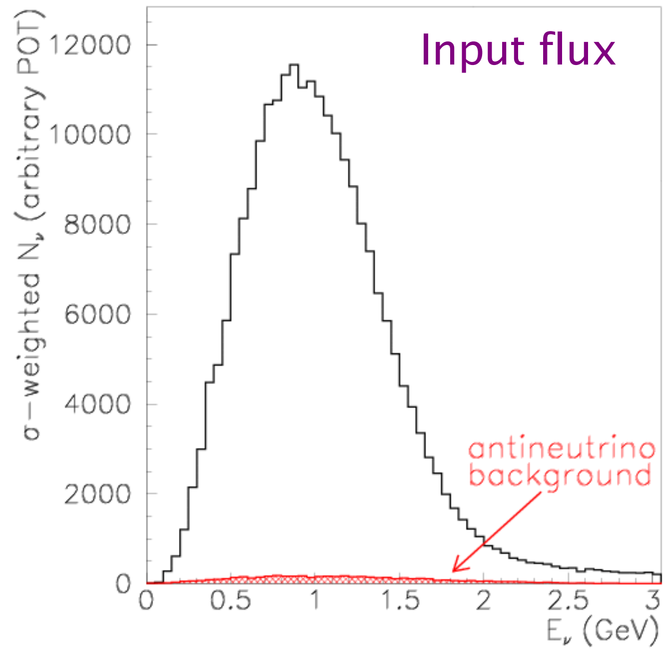
Analysis Chain: X−Section Model

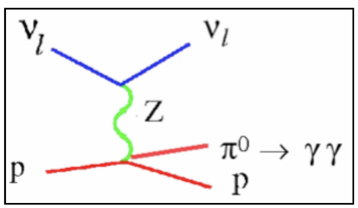


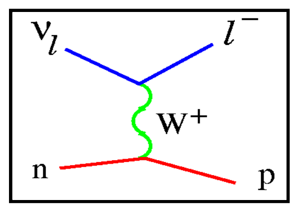
Nuance Monte Carlo

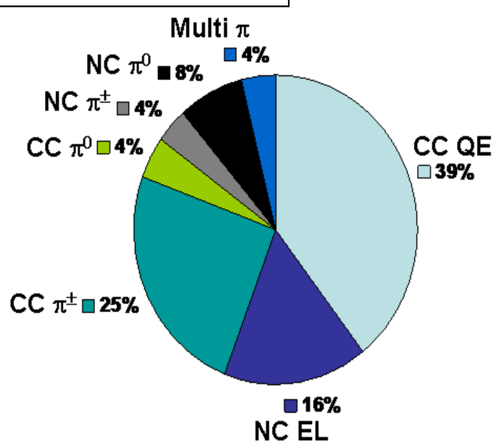
D. Casper, NPS, 112 (2002) 161

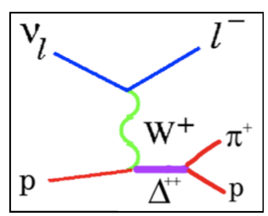
- Comprehensive generator, covers entire E_ν range
- Predicts rates and kinematics of specific ν interactions from input flux
- Expected interaction rates in MiniBooNE (before cuts) shown below
- Based on world data, ν_μ CC shown below right

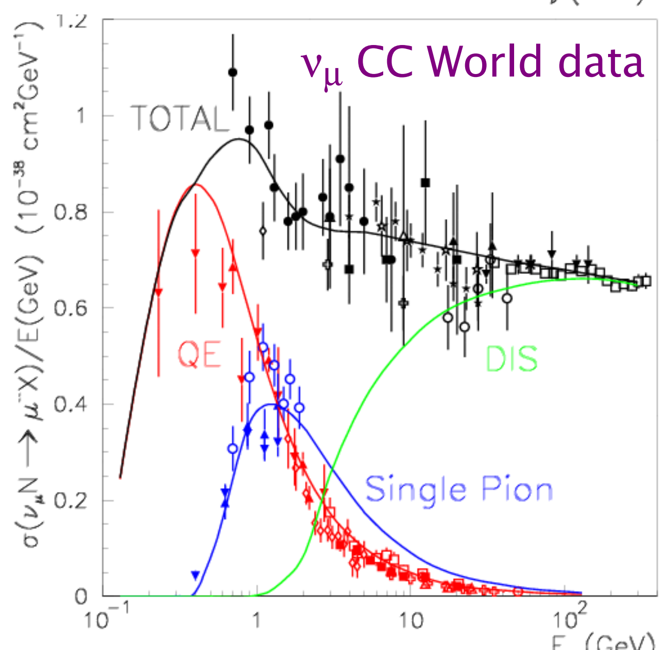












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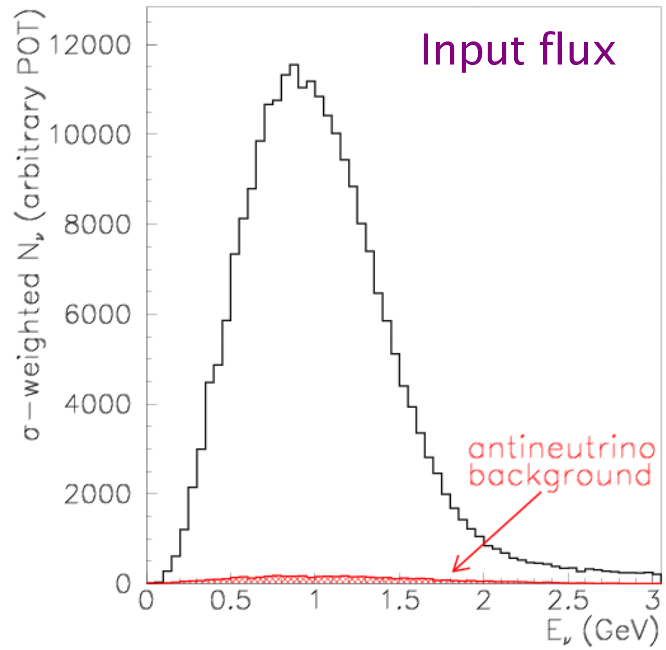
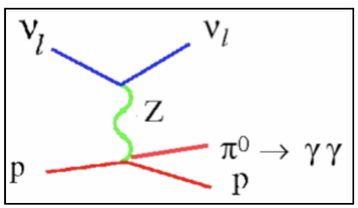
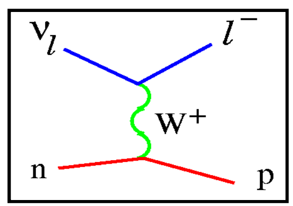
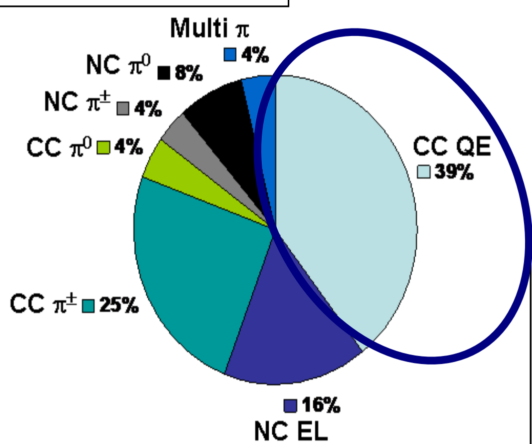
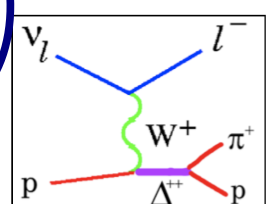
- Also tuned on internal data

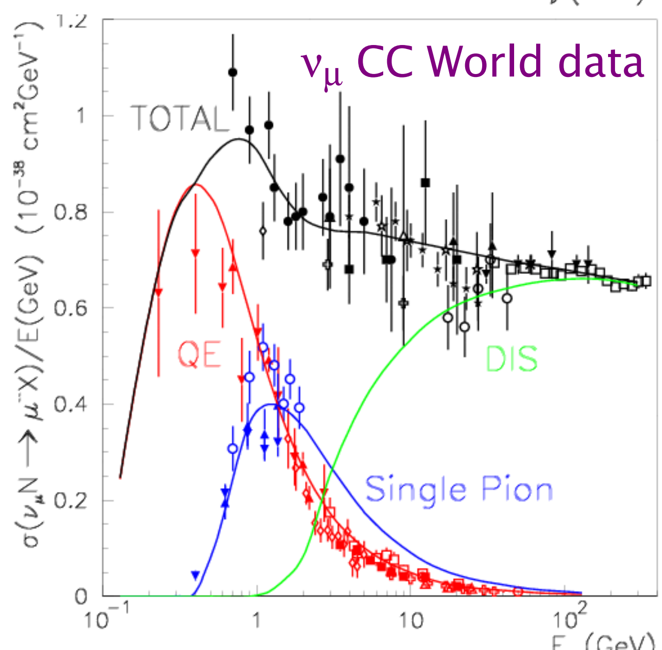




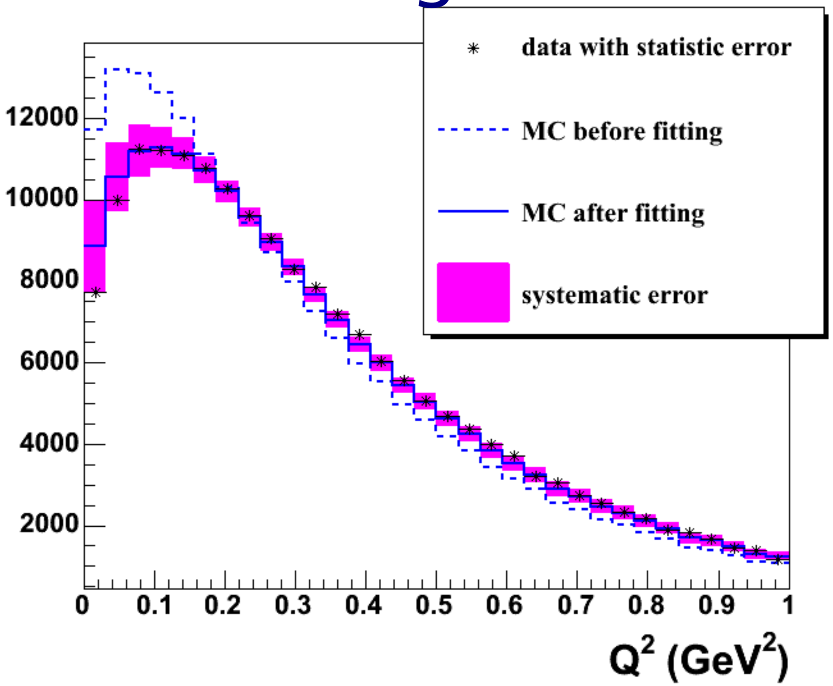




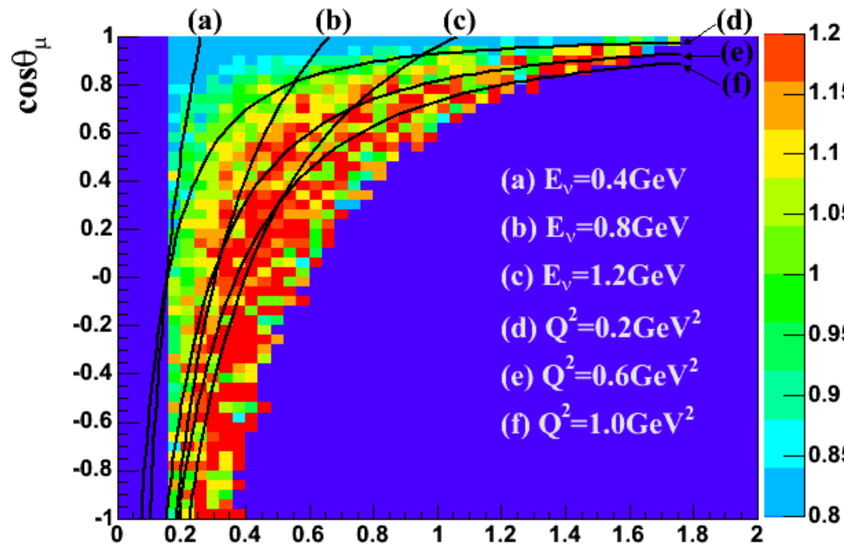




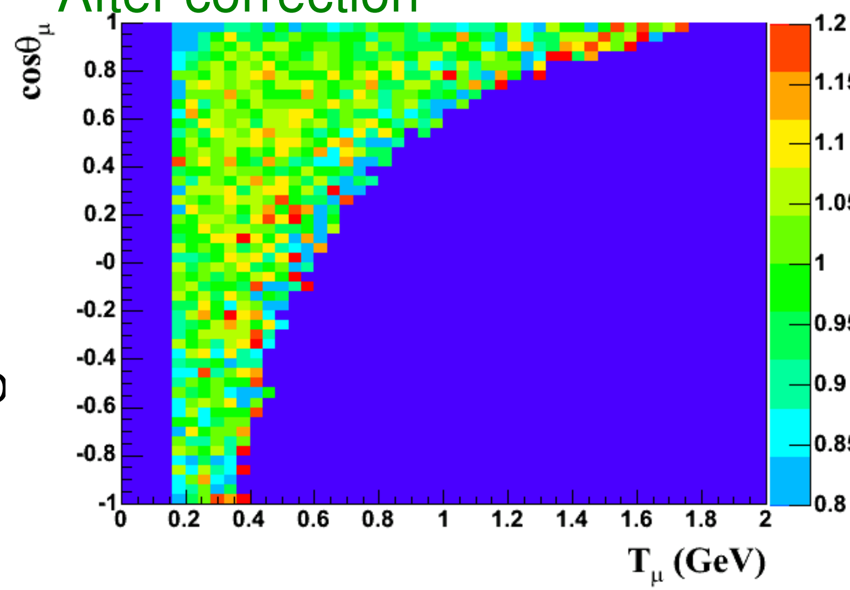
Tuning Nuance on internal ν_μ CCQE data



Before correction



After correction

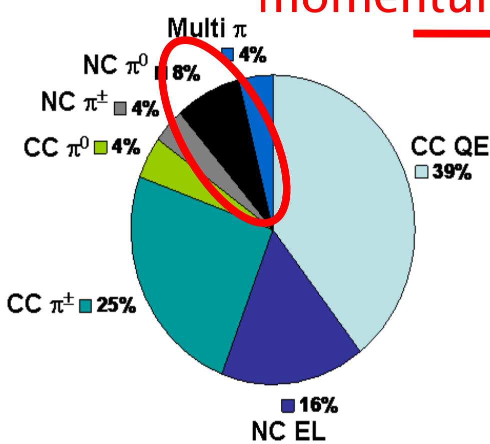


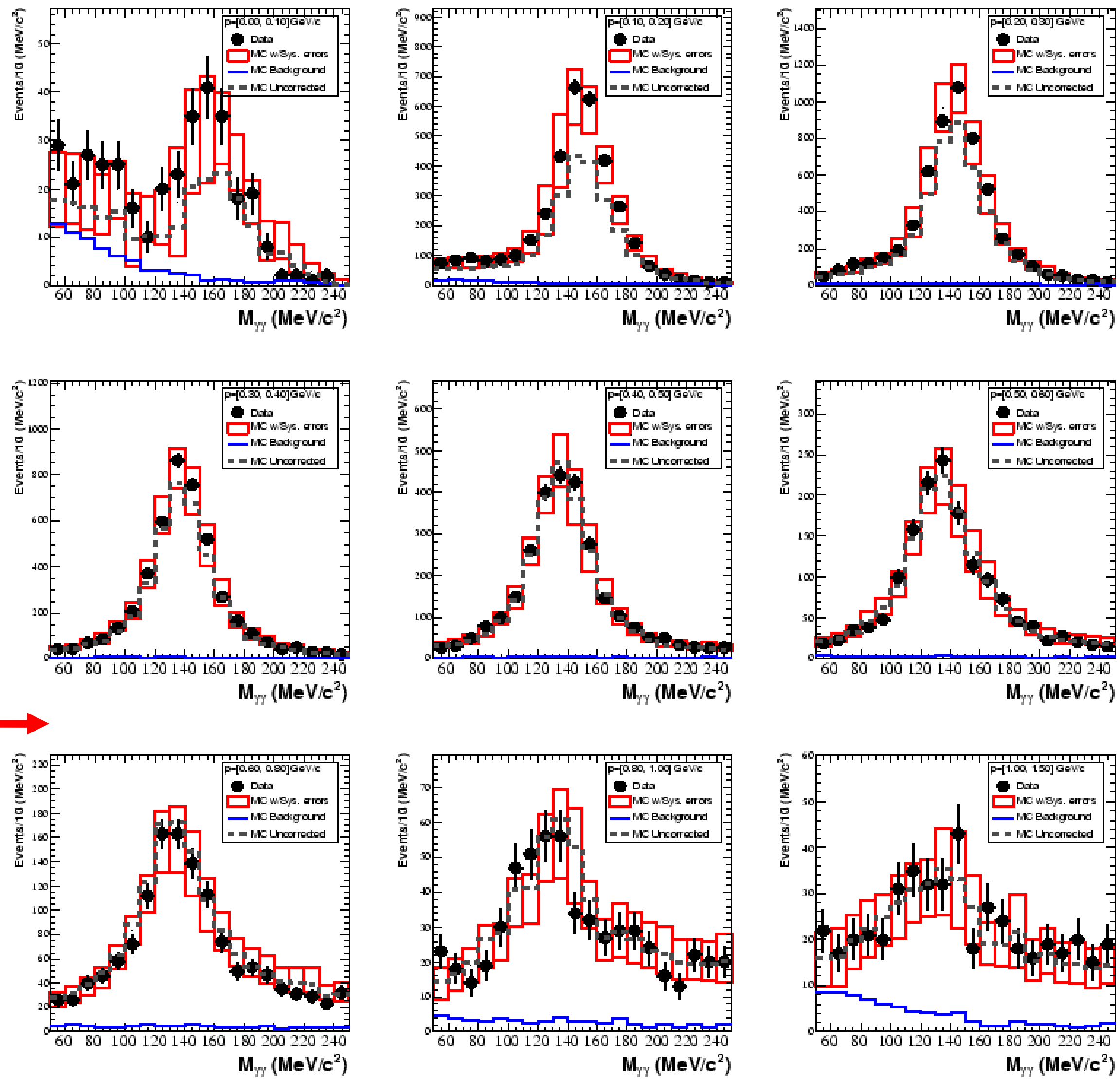
- Poor agreement in Q^2
- From Q^2 fits to MB ν_μ CCQE data extract:
  - M_A^{eff} -- effective axial mass
  - κ -- Pauli Blocking parameter
- Beautiful agreement after Q^2 fit, even in 2D
- Ability to make these 2D plots is unique due to MiniBooNE's high statistics

Tuning Nuance on internal NC π^0 data

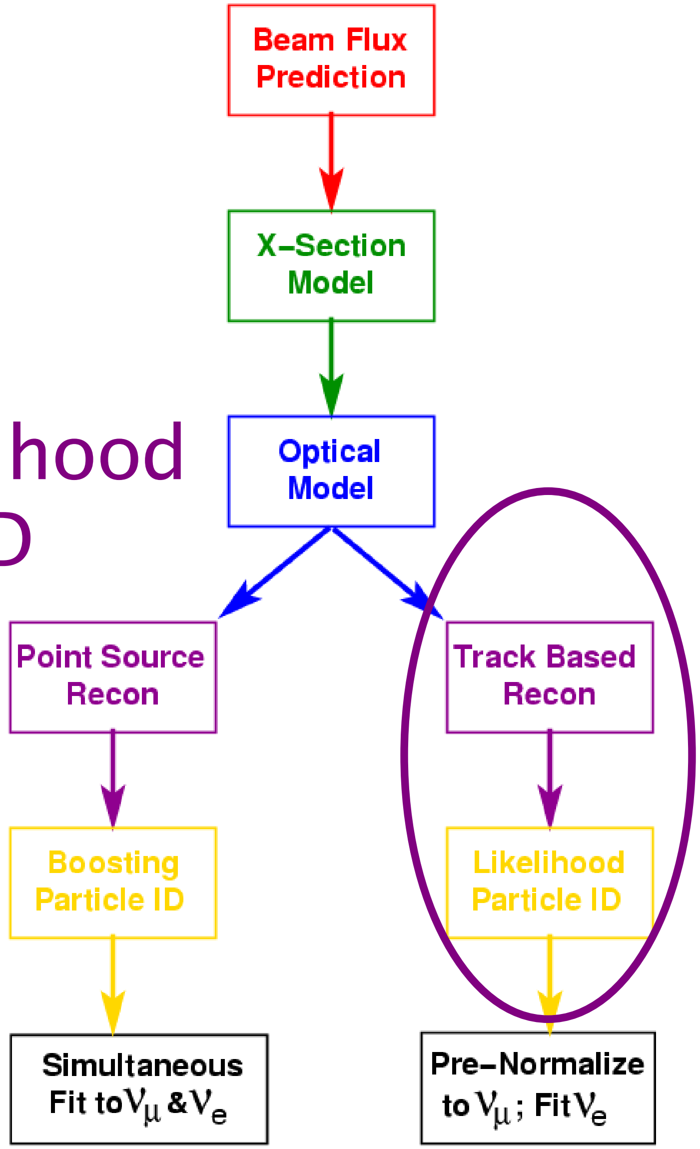
- NC π^0 important background
- 97% pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)
- Measure rate as function of momentum
- Default MC underpredicts rate at low momentum
- $\Delta \rightarrow N\gamma$ also constrained

Invariant mass distributions in momentum bins



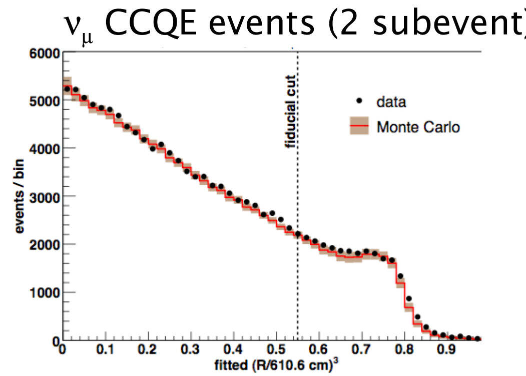


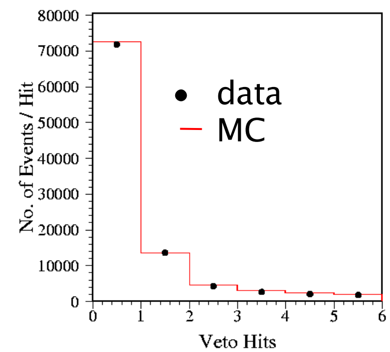
Analysis Chain: Track-Based Likelihood Reconstruction and Particle ID

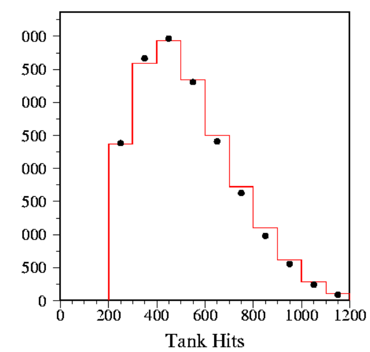


TBL Analysis: Separating e from μ

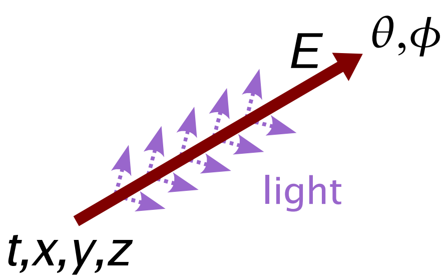
- Analysis pre-cuts
  - Only 1 subevent
  - Veto hits < 6
  - Tank hits > 200
  - Radius < 500 cm

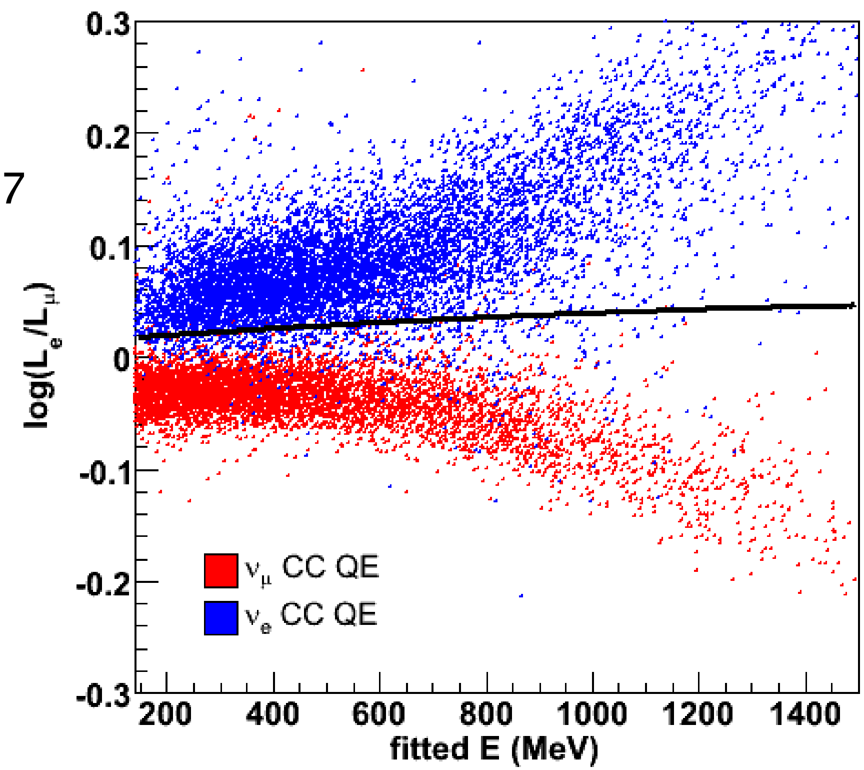






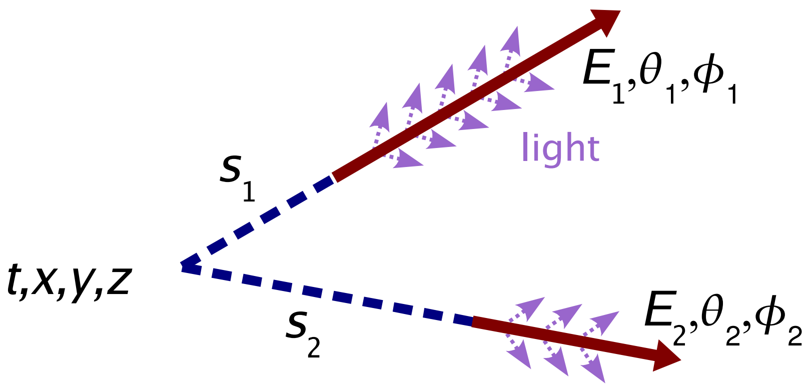
- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon

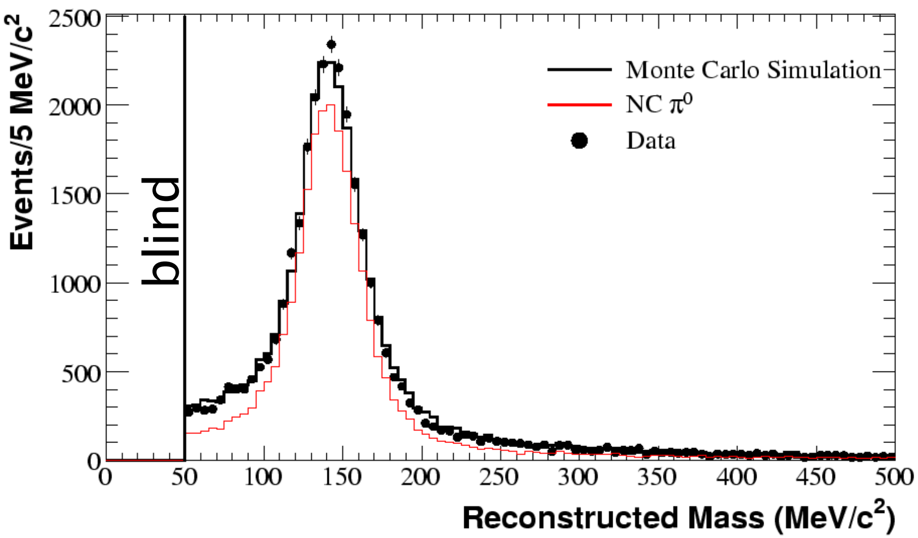


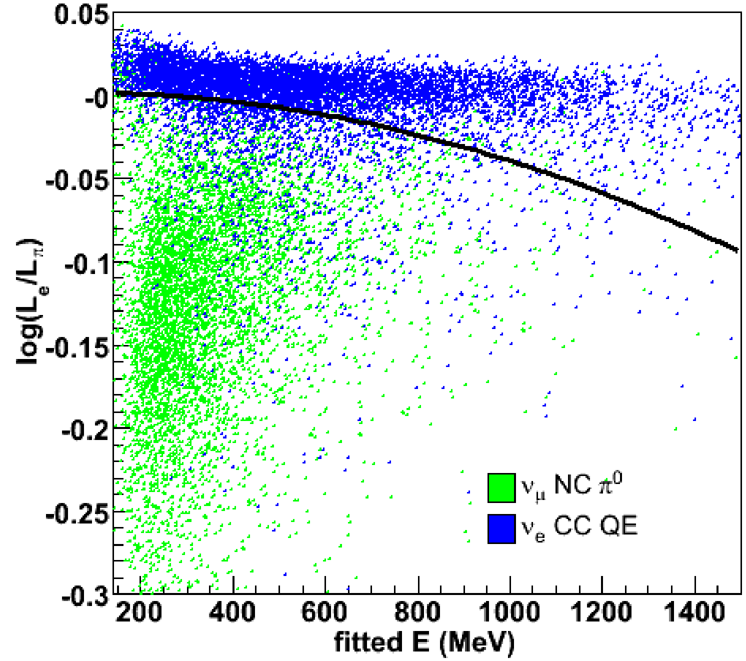


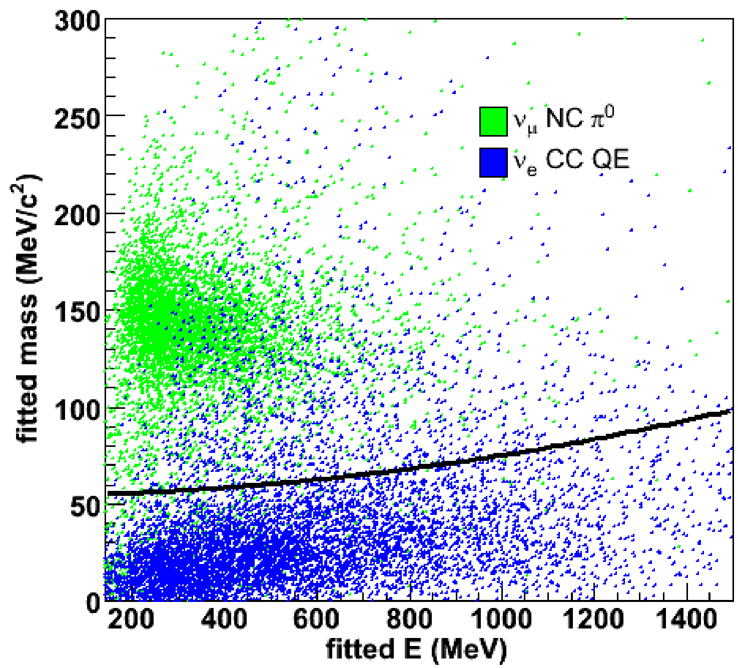
Separating e from π^0

- Extend fit to include two e-like tracks
- Very tenacious fit…8 minutes per event
- Nearly 500k CPU hours used (thanks OSG!)

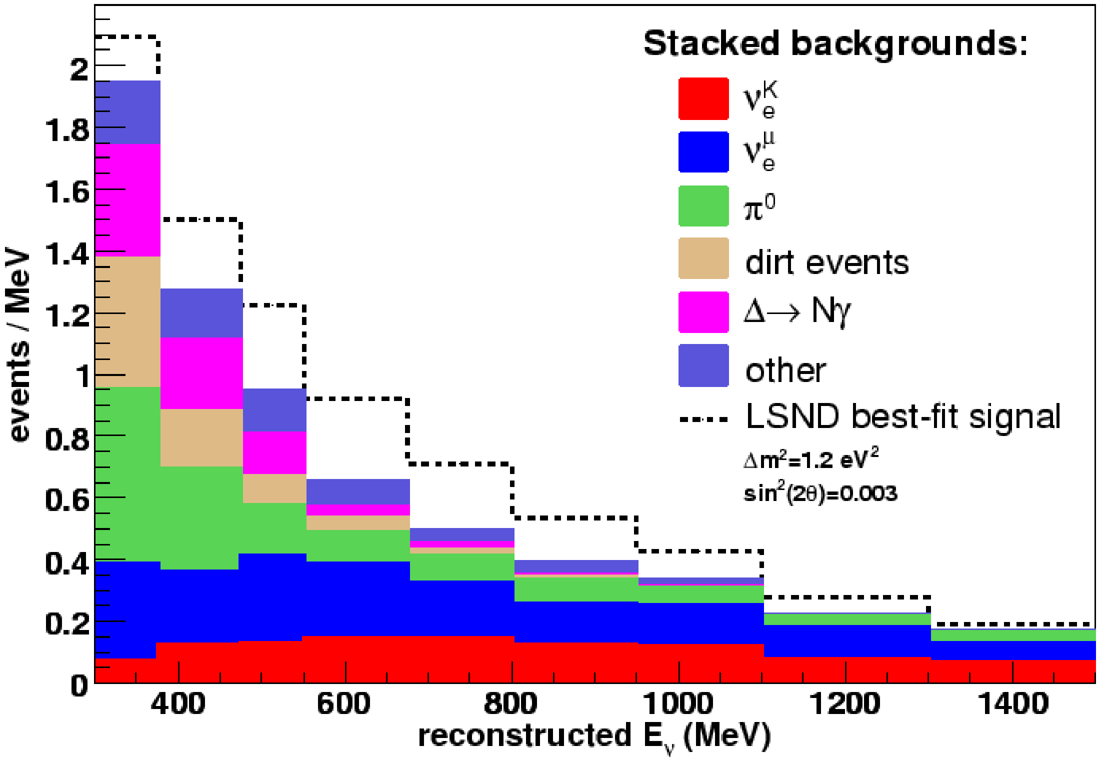








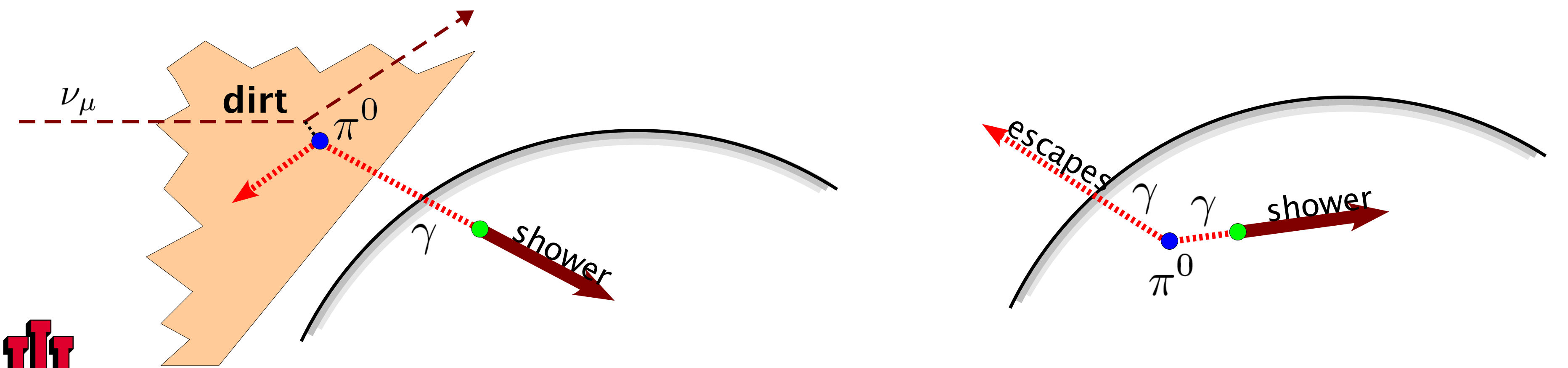
TBL Analysis: Expected event totals



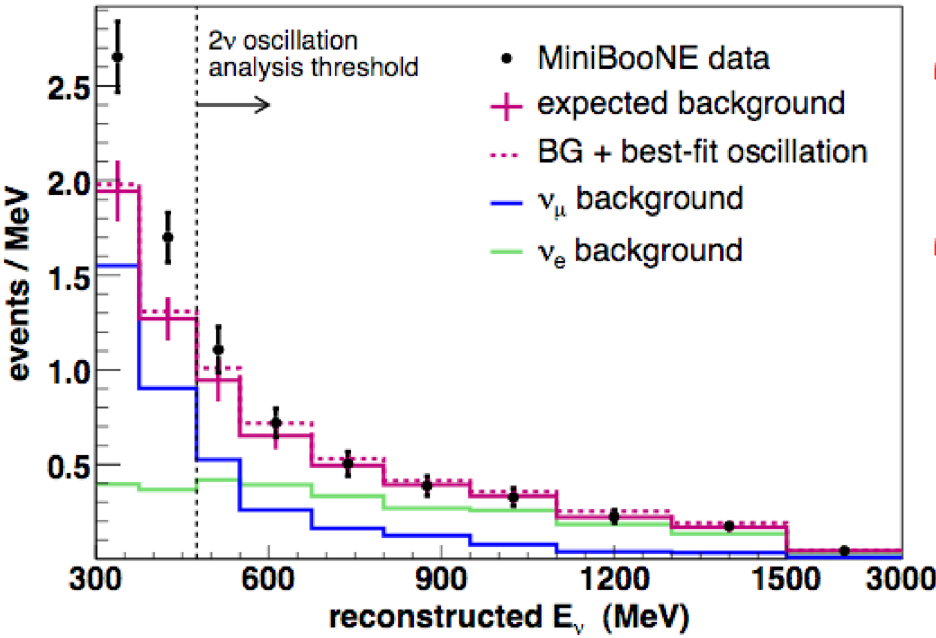
475 MeV – 1250 MeV

ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358

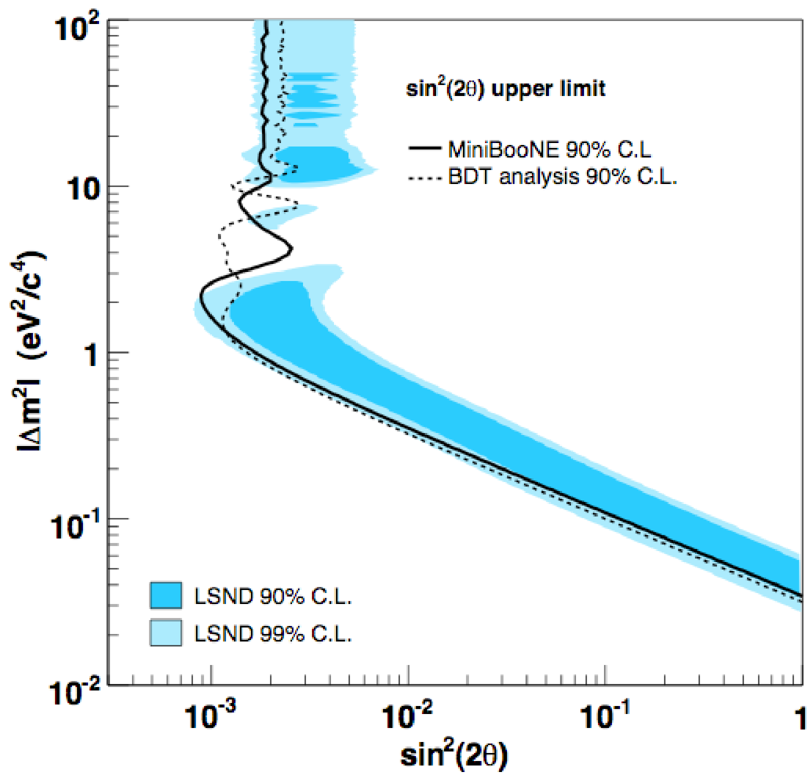
LSND best-fit $\nu_\mu \rightarrow \nu_e$ 126



Data/fit result after blind analysis complete...



- No sign of an excess in the analysis region (where the LSND signal is expected for the 2ν mixing hypothesis)
- Visible excess at low E



- What does it all mean? There are a few possibilities...
  - Some problem with LSND, e.g. mis-estimated background?
  - Difference between neutrinos and antineutrinos?
  - The physics causing the excess in LSND doesn't scale with L/E?
    - Low E excess in MB related?

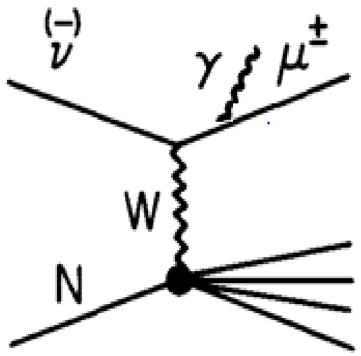
Exploring the Low E Excess

The low E excess has fueled much speculation...

Commonplace

- Muon bremsstrahlung

(Bodek, 0709.4004)

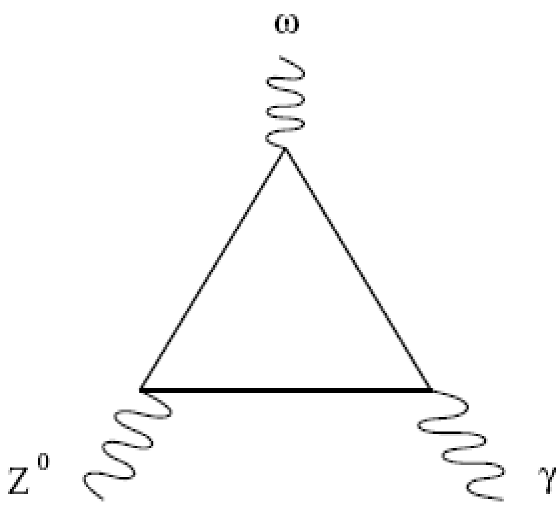


- Easy to study in MB with much larger stats from events with a Michel tag
- Proved negligible with MB data in 0710.3897

SM, but odd

- Anomaly-mediated γ

(Harvey, Hill, Hill, 0708.1281)

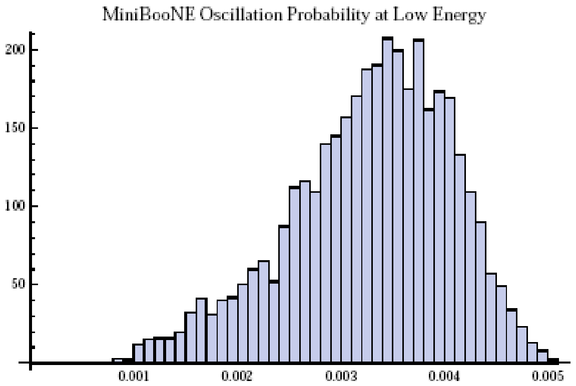


- Still under study, nuc. effects neglected, δg_ω
- Has to contribute...how much?

Beyond the SM

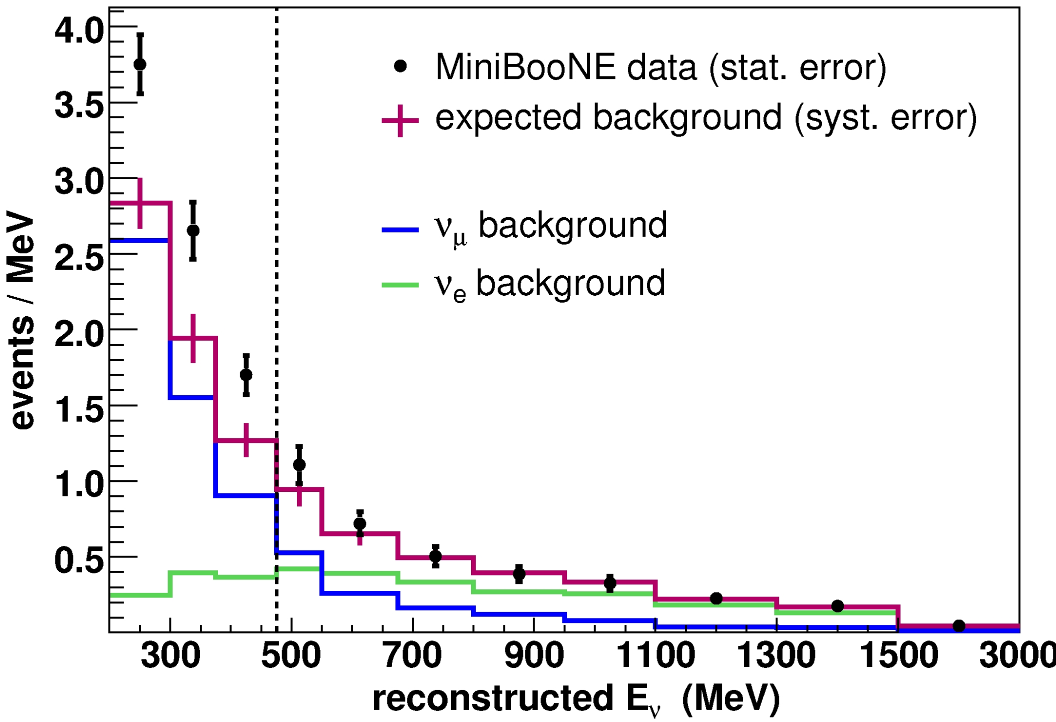
- New gauge boson

(Nelson, Walsh,0711.1363)



- Can accommodate LSND and MiniBooNE
- Firm prediction for anti-neutrinos

Extending the analysis to lower energies



- Original excess quoted in initial oscillation PRL 98, 231801 (2007)
  - 475–1250 MeV, 22 ± 40, 0.6σ
  - 300–475 MeV, 96 ± 26, 3.7σ
- In summer 2007 extended analysis down to 200 MeV
  - 200–300 MeV, 92 ± 37, 2.5σ
- Combined significance with proper systematic correlations
  - 200–475 MeV, 188 ± 54, 3.5σ

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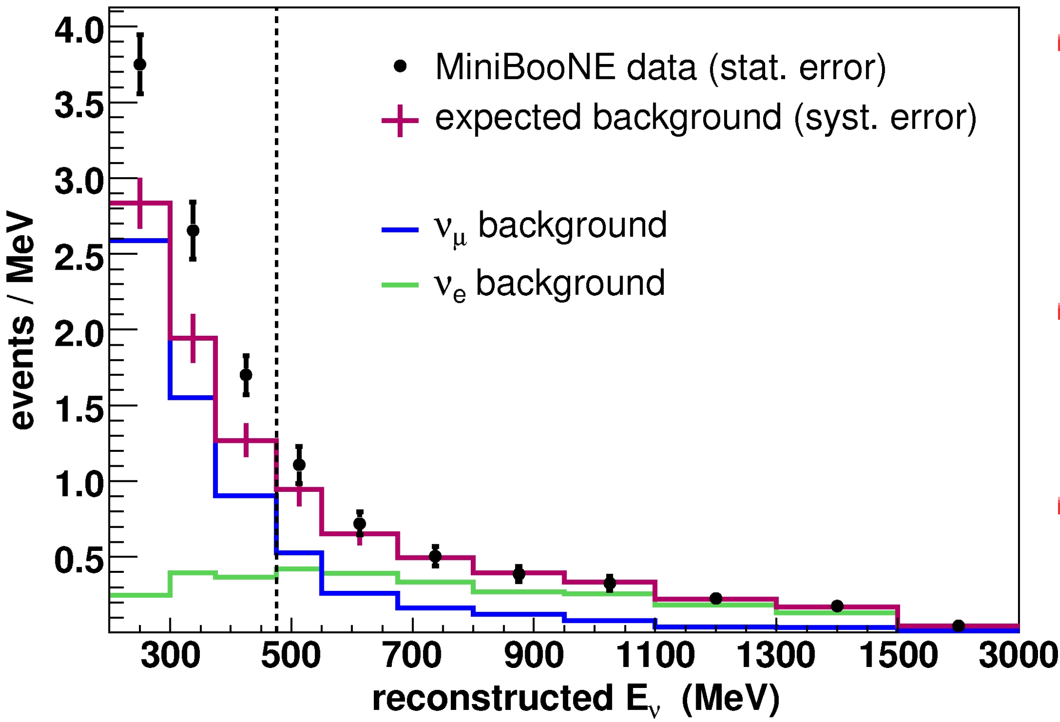

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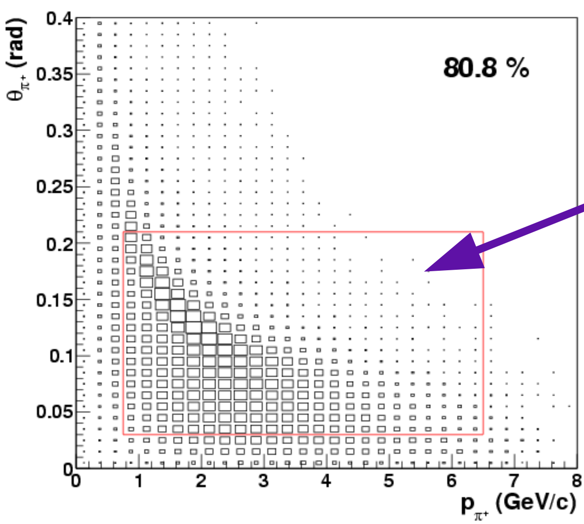
- Might have seen this presented in past with some caveats...
- Work was underway for a comprehensive review bkgs/errors (emphasis at low E), but also wanted to rapidly respond to inquiries about excess below 300 MeV.
- Starting with this talk...no more disclaimers. PRL draft already circulating that covers ~1 year of very careful follow-up work.

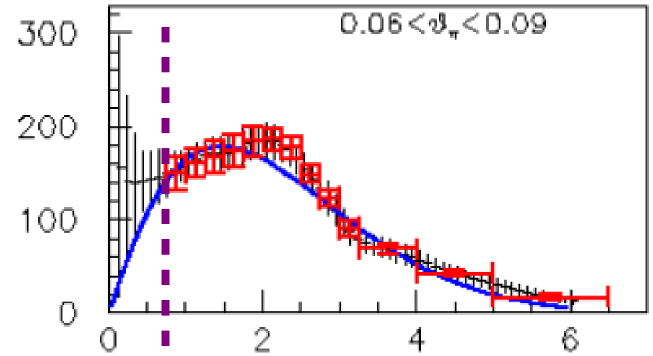
Update #1: Treatment of π flux errors

OLD METHOD:

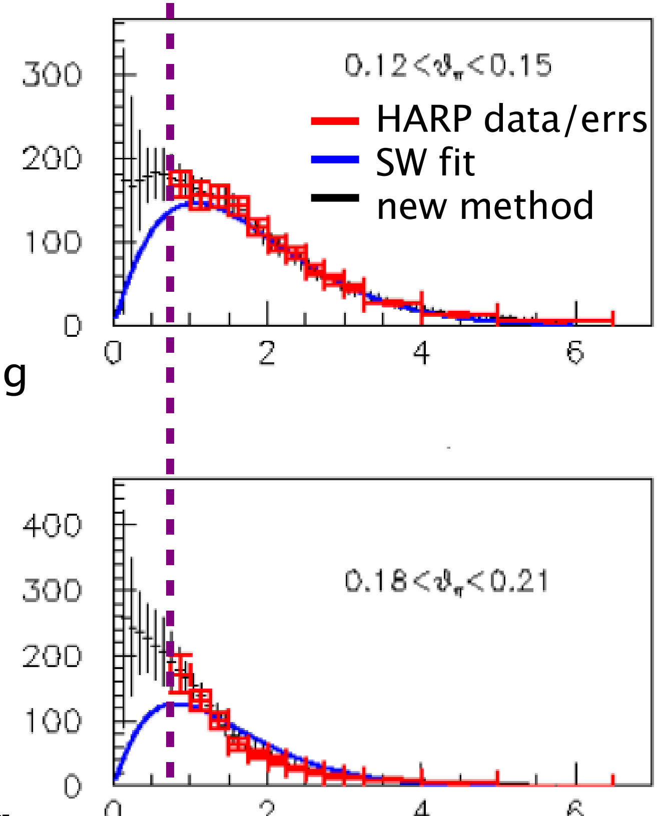
- Fit HARP/E910 data to SW parameterization.
  - Use SW fit as central value (CV) MC
  - Use covariance matrix governing SW parameters in χ^2 fit to assess error
- Problem: poor χ^2 due to SW parameterization not fully describing data at HARP's precision
- Old Sol'n: inflate HARP error until χ^2 accept.
- Turns HARP's ~7% error into ~15%



81% of ν flux crossing MB covered by HARP



xsec (mb) vs p_π (GeV)



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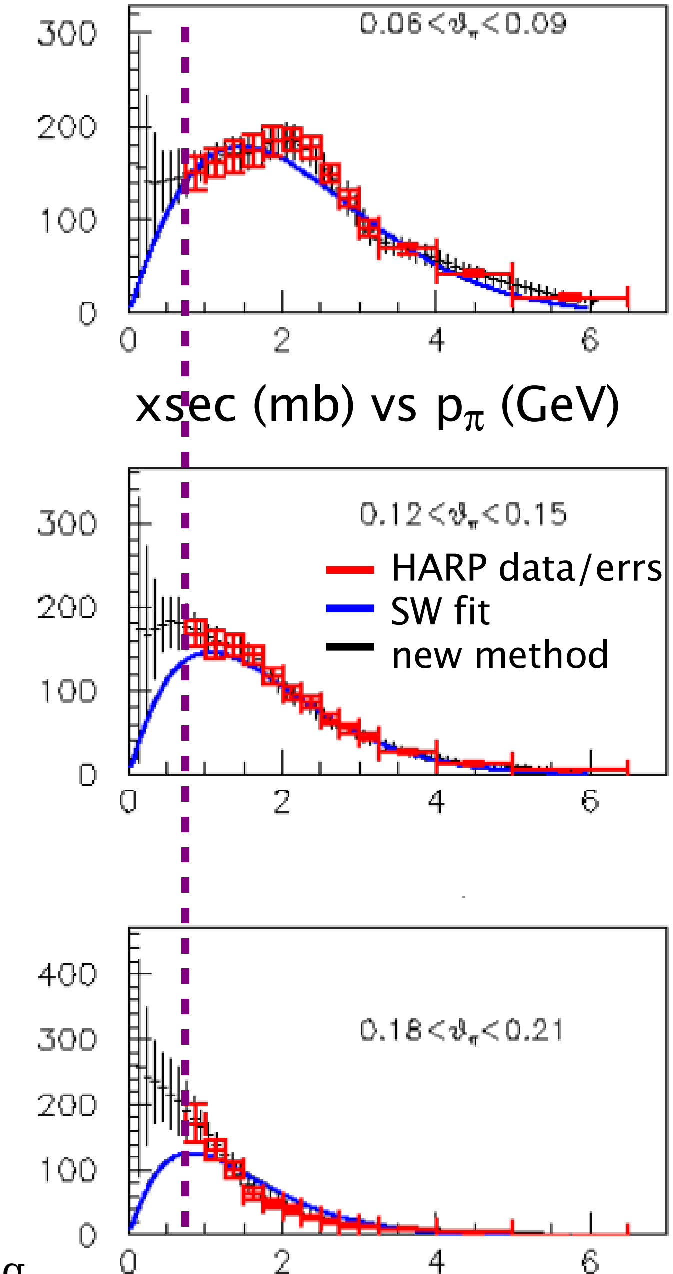
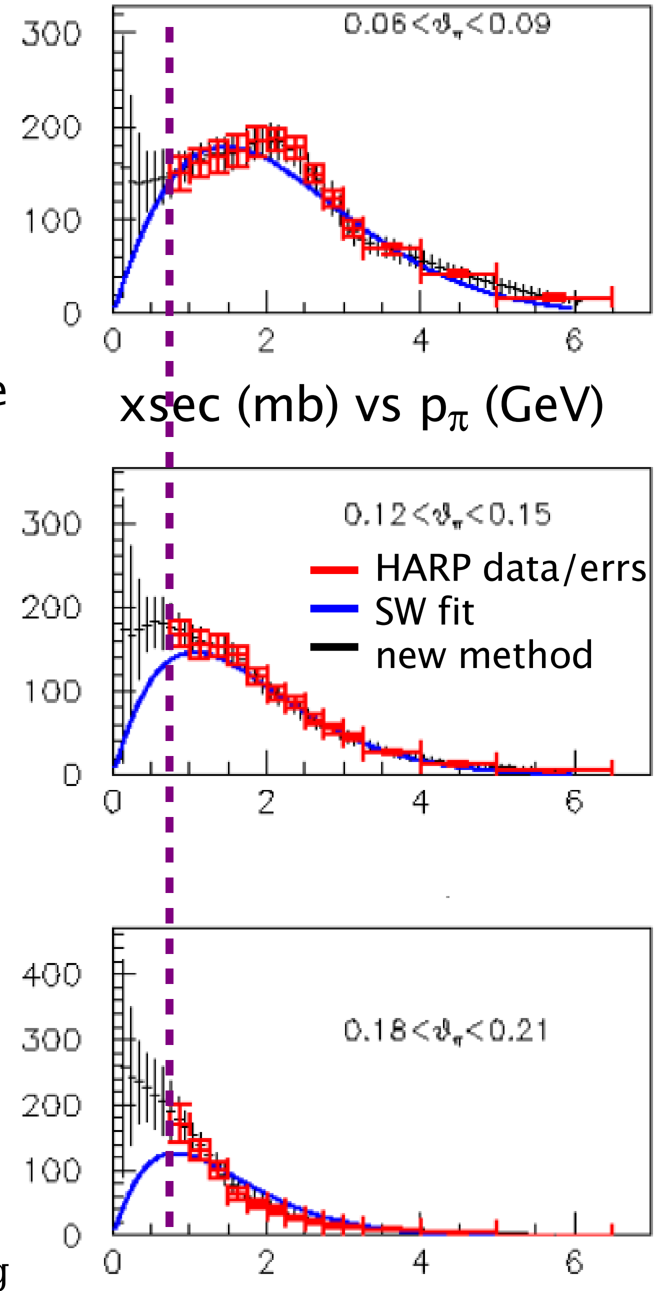
- Sounds dumb, but...
  - Getting a good 2-dim parameterization in (p,θ) not as easy as you might think
  - Totally unimportant for ν_e appearance where the π flux is heavily constrained from the *in situ* ν_μ measurement



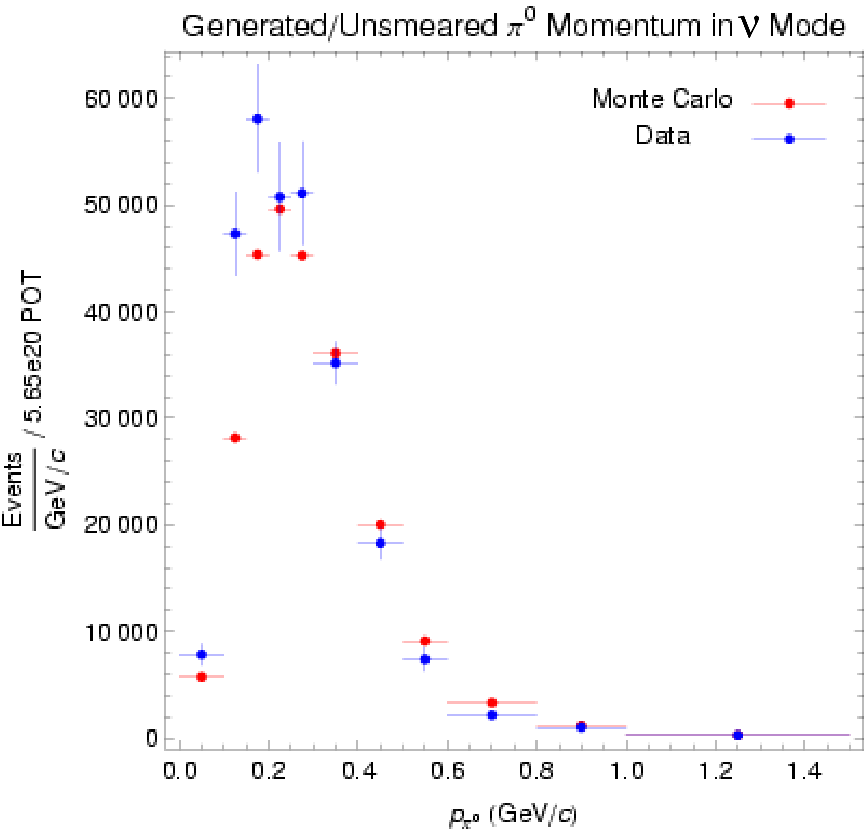
Update #1: Treatment of π flux errors

NEW METHOD:

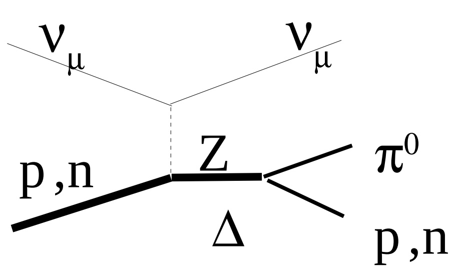
- Forget SW, use HARP data and fit with spline interpolation
- Vary HARP data with their own covariance matrix to produce flux systematic error
- Update #1 bottom line: No impact on ν_e appearance
  - Largest diff at low p_π ,not much ν flux hitting det, further deweighted by cross-sections
  - Still have additional 5% in errors coming from horn modeling + secondary interactions



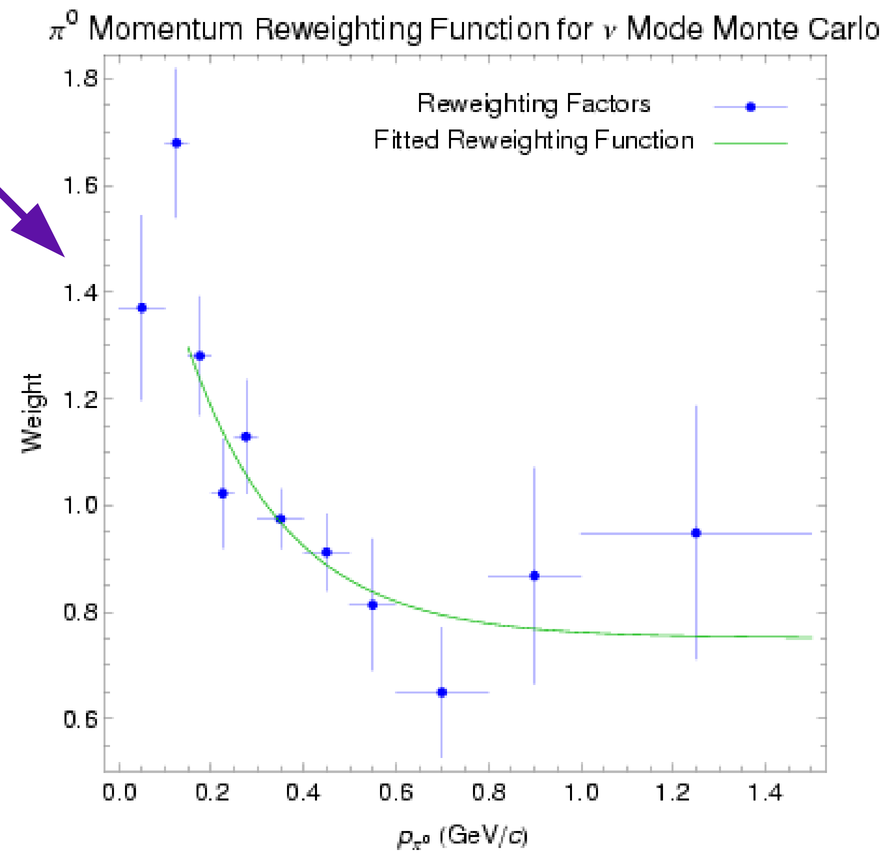
Update #2: Improved π^0/radiative Δ analysis



$\nu_\mu(p,n)\rightarrow\nu_\mu(p,n)\pi^0, \pi^0\rightarrow\gamma\gamma$



- Complete re-extraction of π^0 weights
  - Independent code, improved unsmearing technique, 11 bins, consistent with old result
  - Fit over 9 bins in p_π to smooth reweighting function



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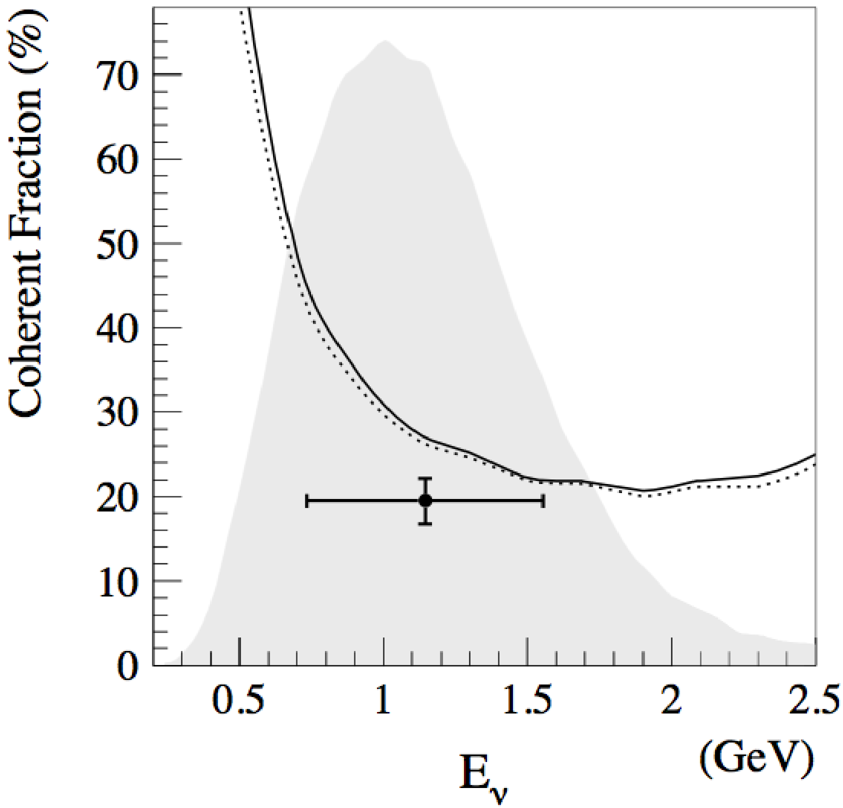
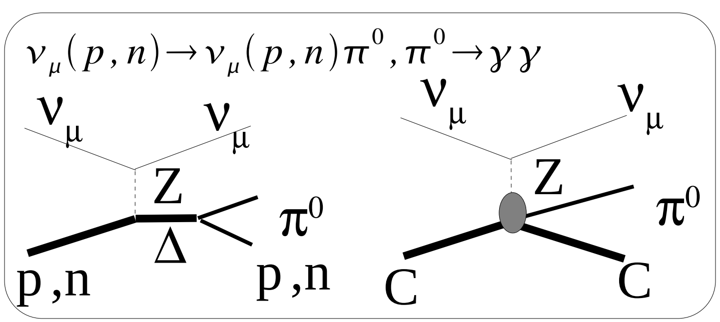




- Applied *in situ* measurement of the coherent/resonant production rate
  - Coherent event kinematics more forward
  - Coherent fraction reduced by 35% (from RS)
- Improvements to Δ->Nγ bkg prediction
  - Coh/res π^0 fraction measured more accurately, Δ->Nγ rate tied to res π^0
  - Old analysis, π created in struck nucleus not allowed to reinteract to make new Δ
  - Complete combinatorial derivation based on branching ratios (Γ_γ, Γ_{π^0}) and the pion escape probability (ε)

$$\frac{N_C(\Delta \rightarrow N\gamma)}{N_C(\Delta \rightarrow N\pi^0)} = \frac{3\Gamma_\gamma}{2\Gamma_{\pi^0}\varepsilon}$$

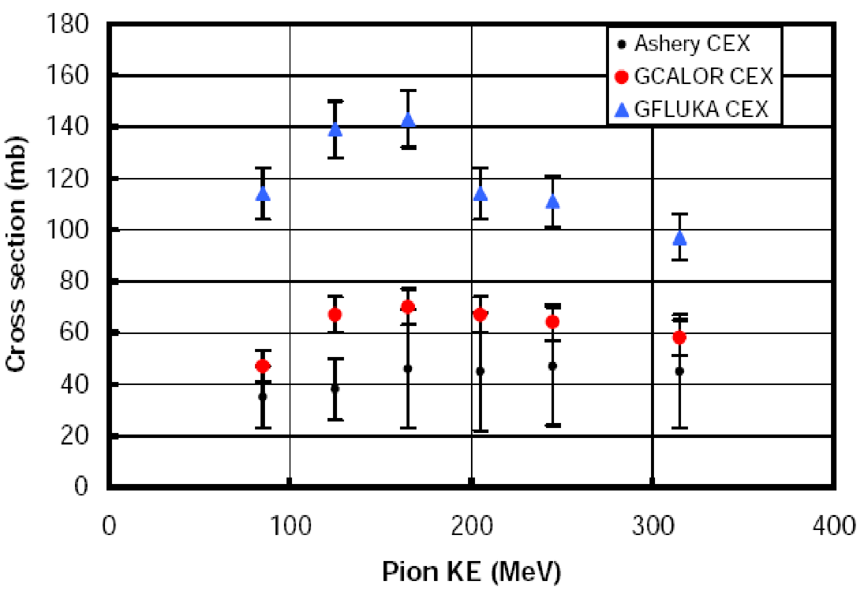
  - Error on Δ->Nγ bkg increased from 9 to 12%
- Update #2 bottom line: Overall, produces a small change in ν_e appearance bkgs

Update #3: Hadronic bkgs/errors in ν interactions

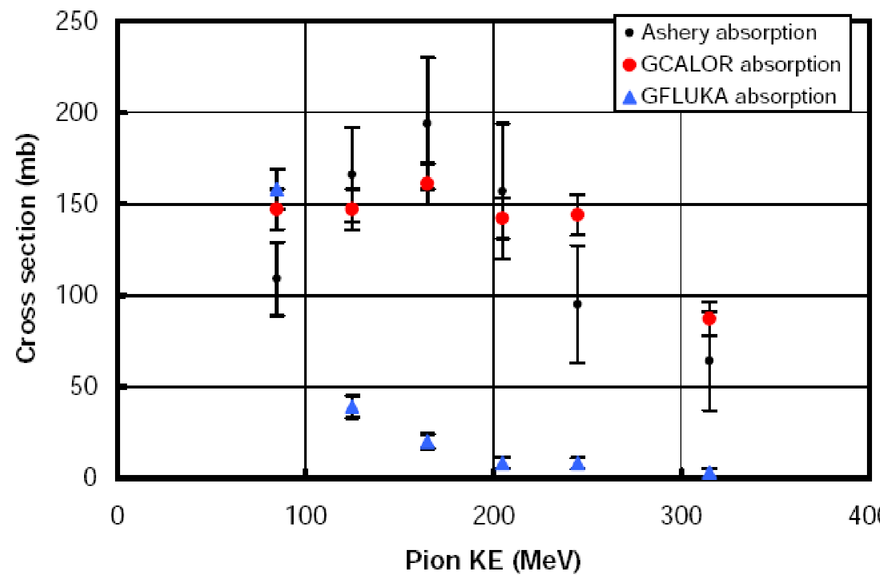
OLD HADRONIC PROCESSES/ERRORS:

- Mainly due to charged π absorption and charge exchange in the mineral oil, analogous to the same processes in the struck nucleus
- Use GEANT3 MC with GCALOR instead of GFLUKA default
  - better π abs/cex handling (error=max{Ashery error,Ashery-GCALOR})
  - better neutron scattering
- Cross-check: Accounting for cex/abs differences GCALOR & GFLUKA give same result for ν_e appearance bkgs

π^+ C single charge exchange



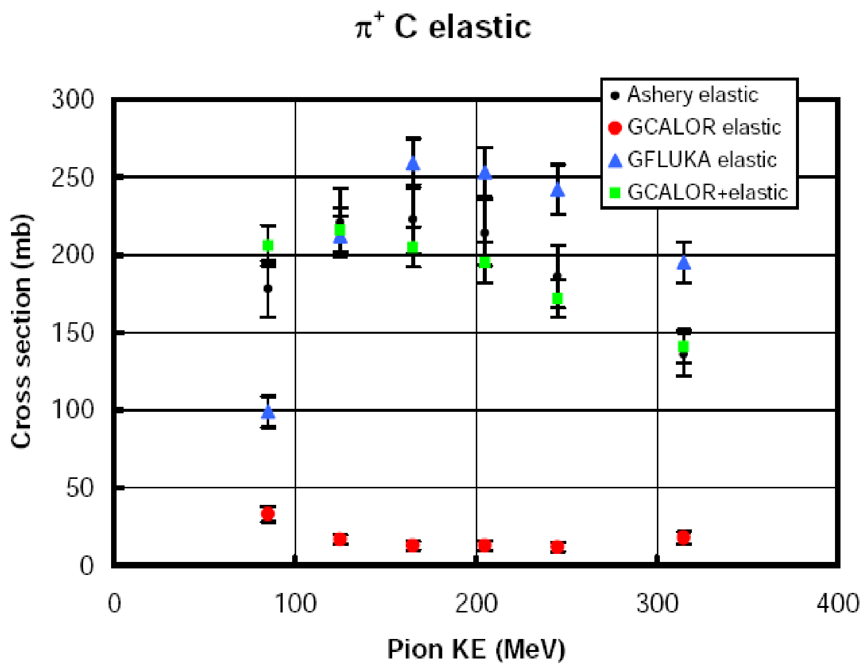
π^+ C absorption (no π out)



Update #3: Hadronic bkgs/errors in ν interactions

ADDITIONAL HADRONIC PROCESSES:

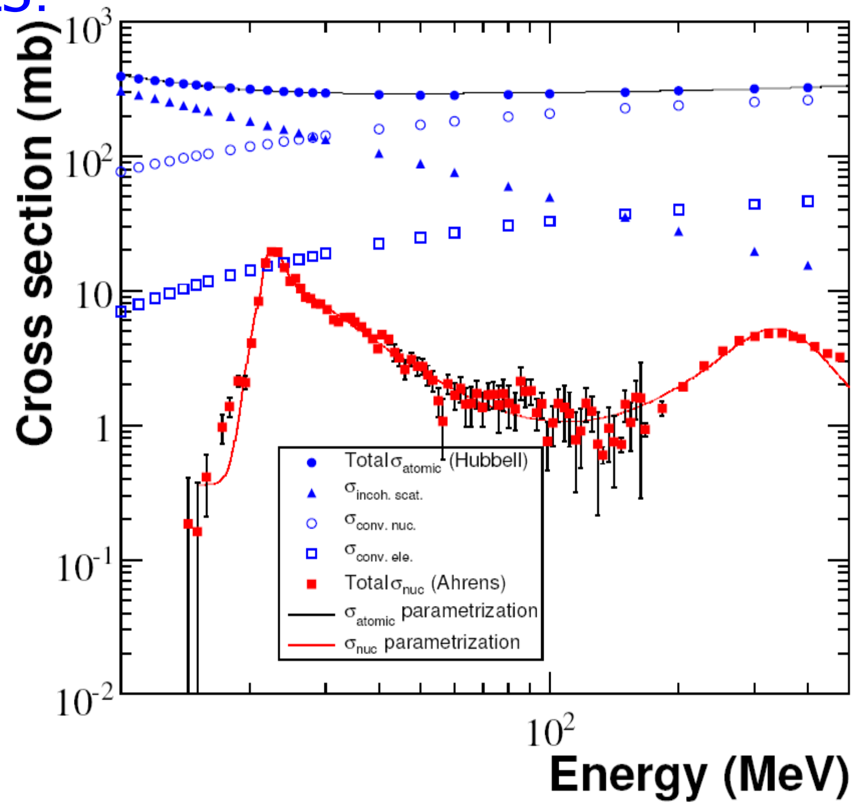
- Charged π – C elastic scattering
  - Found $\pi^\pm$ elastic scattering to be nearly absent in GCALOR
  - Possibility that NC $\pi^\pm$ have more scattering ⇒ making Cerenkov ring look more e-like
- Radiative π^- capture
  - π^- capture is in GCALOR, but missing radiative branching fraction (<2%, ~100MeV gamma)
- $\pi^\pm$ induced Δ->Nγ
  - Abs/cex allowed in GCALOR, but radiative γ branch missing
  - Not as dangerous as in struck nucleus, since π propagates for some time and can give multiple rings
- None of these processes contributed a significant number of bkg events.



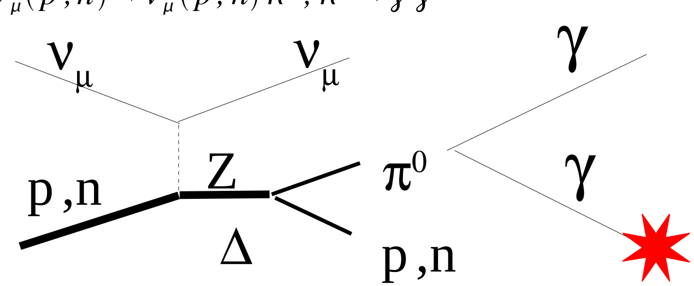
Update #3: Hadronic bkgs/errors in ν interactions

ADDITIONAL HADRONIC PROCESSES:

- Photonuclear interactions
  - Absent in GEANT3
  - Can delete a γ in a NC pi0 interactions, thus creating a single e-like ring
  - 40,000 NC pi0 interactions
  - Well-known cross-section, in fact in GEANT4 which allowed for cross-check
  - Uncertainties enter via final states
- Only hadronic process found to contribute significantly



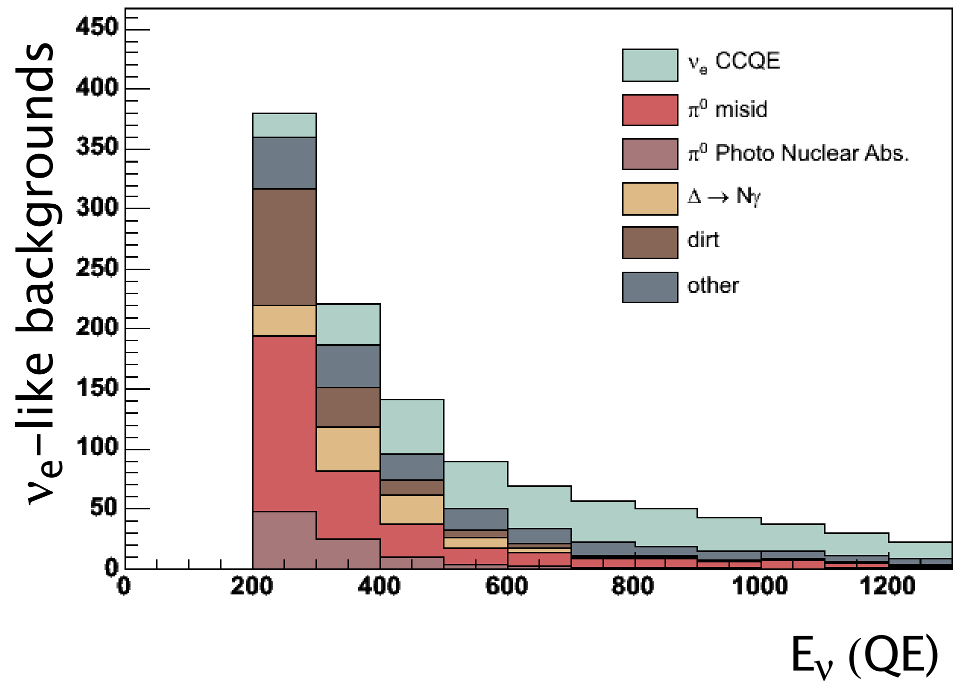
$$\nu_\mu(p,n)\rightarrow\nu_\mu(p,n)\pi^0,\pi^0\rightarrow\gamma\gamma$$



Update #3: Hadronic bkgs/errors in ν interactions

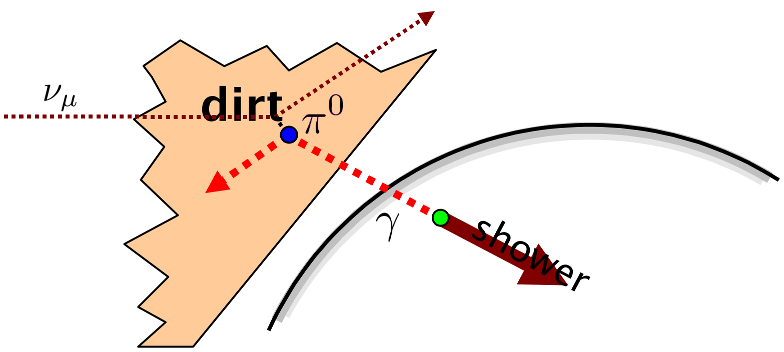
ADDITIONAL HADRONIC PROCESSES:

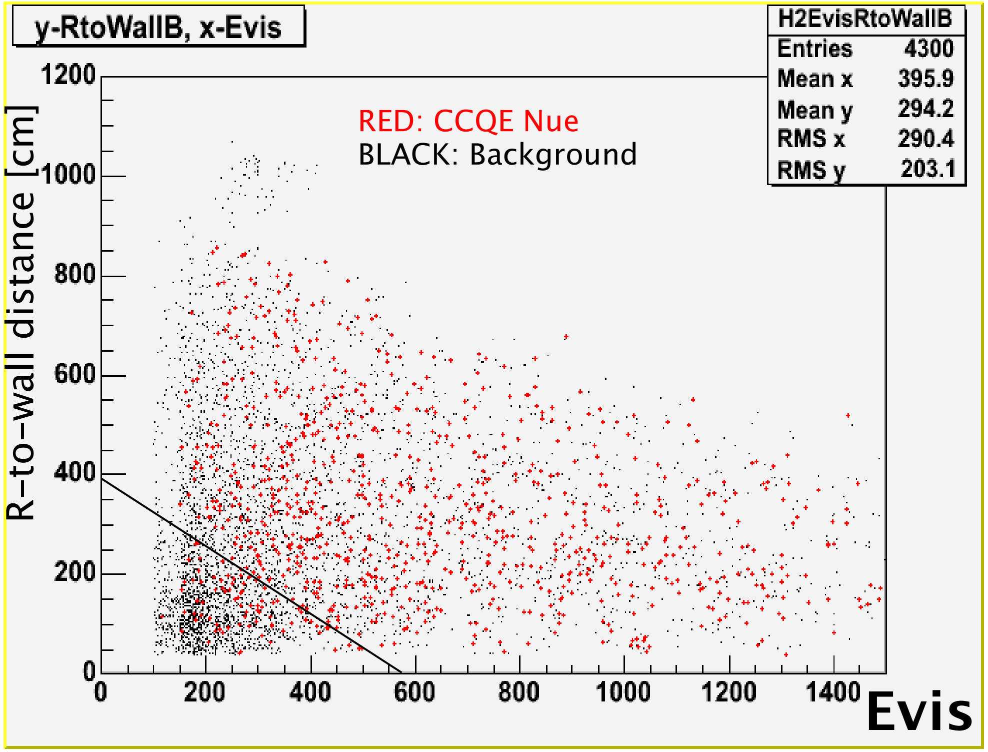
- Update #3 bottom line:
  - Additional p0 mis-id due to all modified hadronic processes (dominated by PN)
    - 200-300 MeV, ~40 events
    - 300-475 MeV, ~20 events
    - 475-1250 MeV, ~1 event
  - Additional systematic error negligible relative to other errors



Update #4: Additional cut to remove dirt events

- Dirt backgrounds tend to come from γ that sneak through the veto and convert in tank ⇒ pile up at high radius
- Don't carry full ν energy ⇒ pile up at low visible energy
- Define R-to-wall cut, distance back to wall along reconstructed track direction
- Apply 2d cut as shown

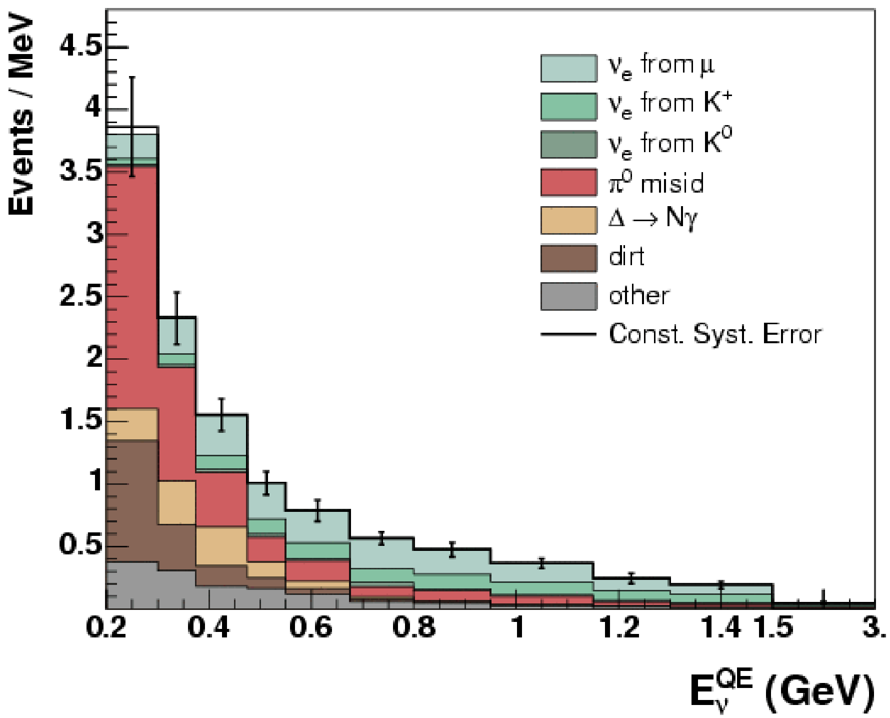




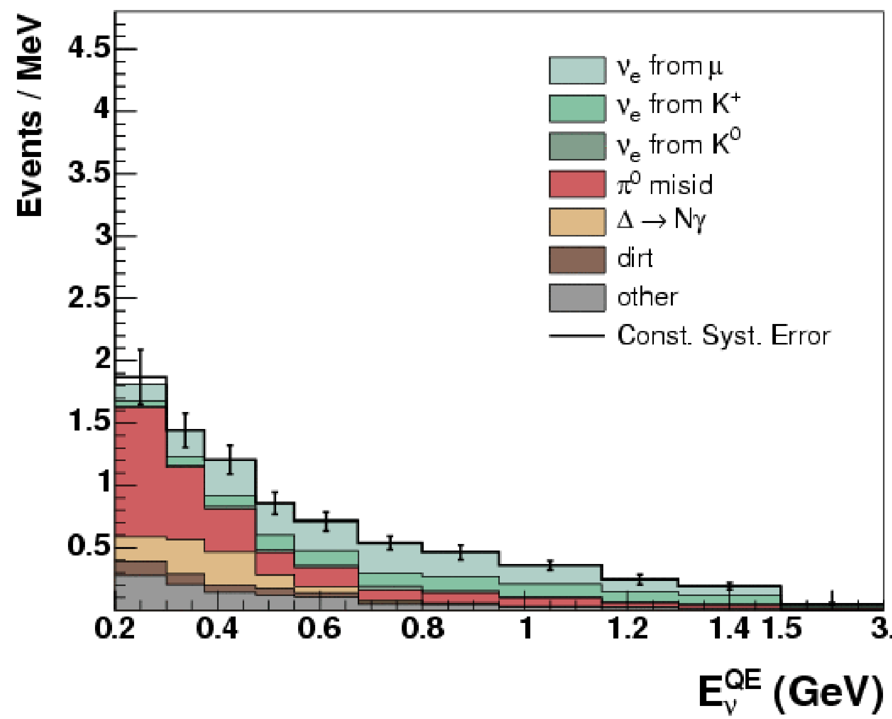
Update #4: Additional cut to remove dirt events

- Update #4 bottom line: Removes ~85% of the dirt backgrounds at low energy

No DIRT cuts

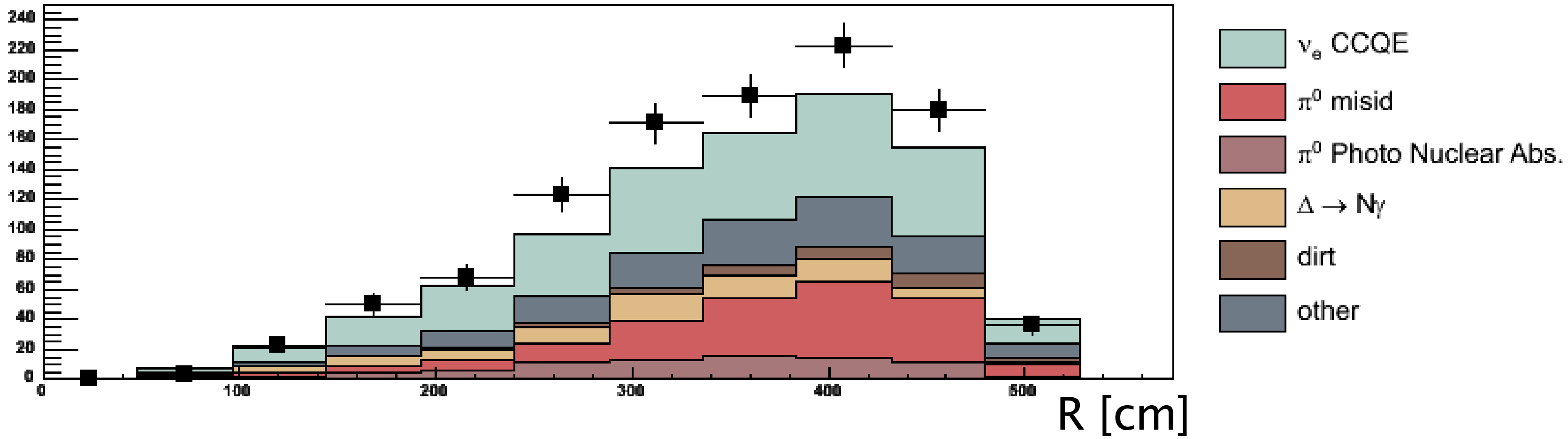


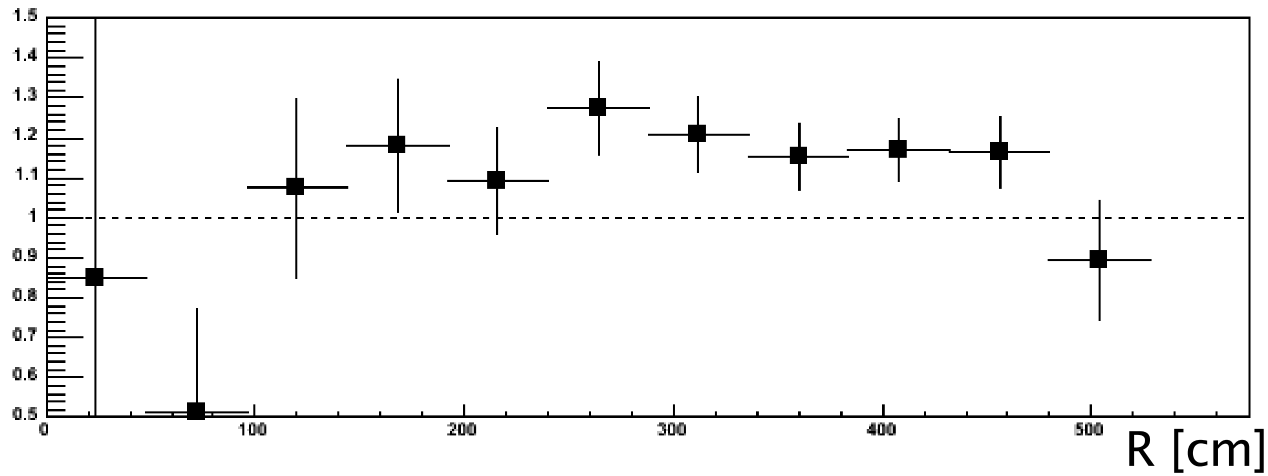
With DIRT Cuts



Update #4: Additional cut to remove dirt events

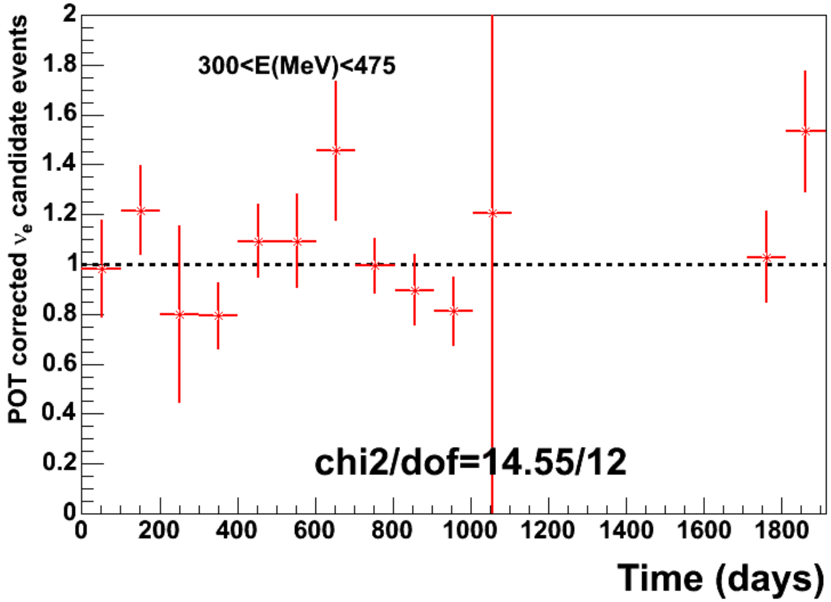
- Consistency-check: look at radial distribution after dirt cut applied
  - Uniform excess throughout tank

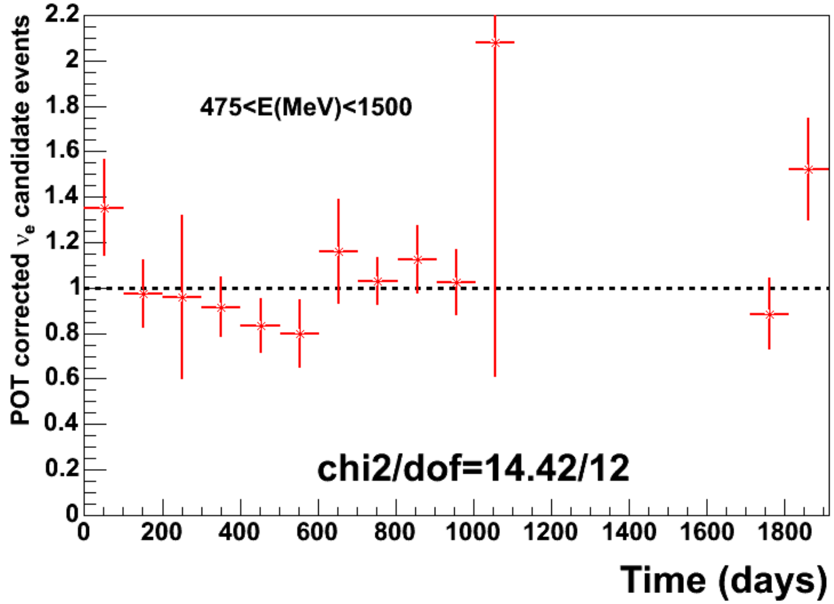




Update #5: New data

- Extra 0.83E20 POT during combined MiniBooNE/SciBooNE ν running
  - ν_e–like events per POT evenly distributed throughout duration of run
- Update #5 bottom line: ν_e–like event rate slightly higher for new data, but perfectly acceptable



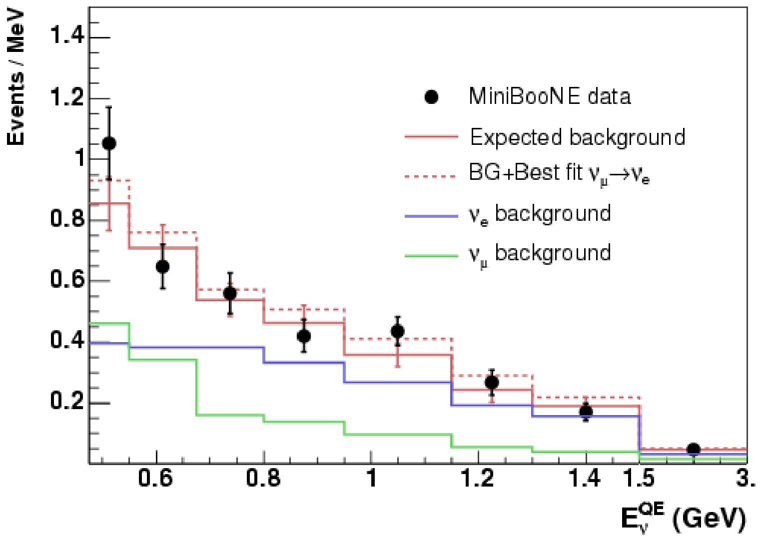


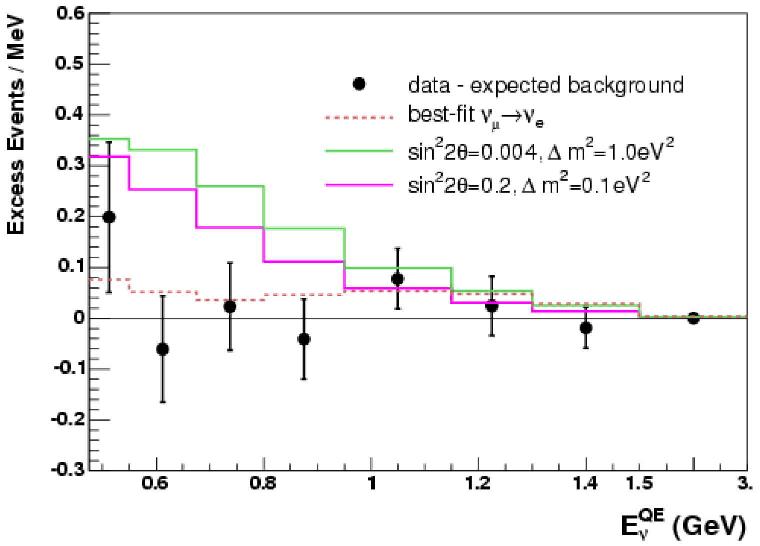
Final Results: Background event breakdown

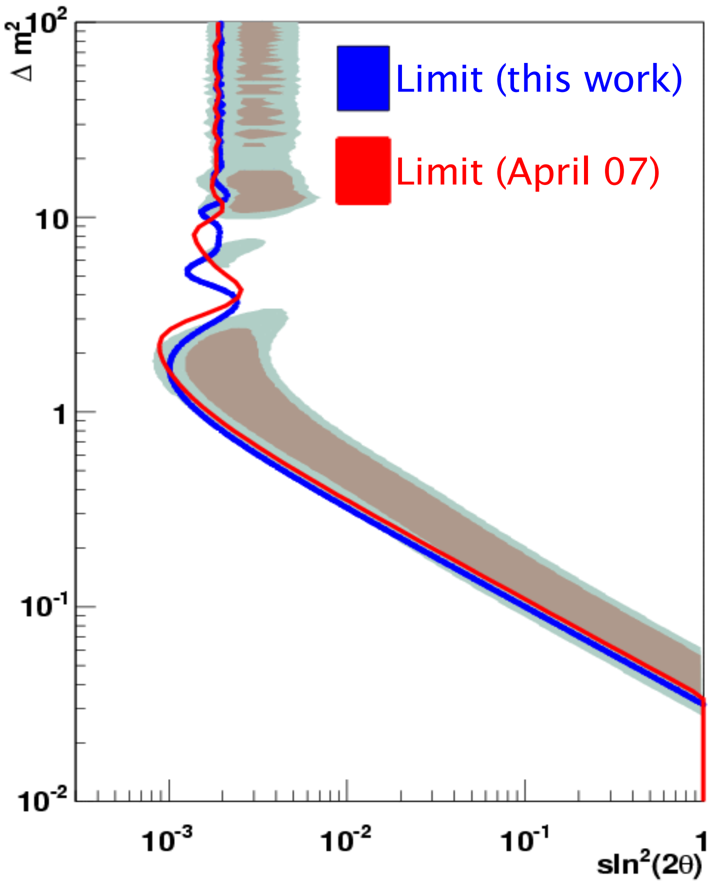
Process	$200 - 300$	$300 - 475$	$475 - 1250$
ν_μ CCQE	9.0	17.4	11.7
$\nu_\mu e \to \nu_\mu e$	6.1	4.3	6.4
NC π^0	103.5	77.8	71.2
NC $\Delta \to N\gamma$	19.5	47.5	19.4
Dirt Events	11.5	12.3	11.5
Other Events	18.4	7.3	16.8
ν_e from μ Decay	13.6	44.5	153.5
ν_e from K^+ Decay	3.6	13.8	81.9
ν_e from K^0_L Decay	1.6	3.4	13.5
Total Background	186.8 ± 26.0	228.3 ± 24.5	385.9 ± 35.7

- Above 475 MeV still dominated by intrinsic nue
- At low E transitions to NC π^0 and Δ->Nγ dominated bkgs

Final Results: Impact on oscillation analysis

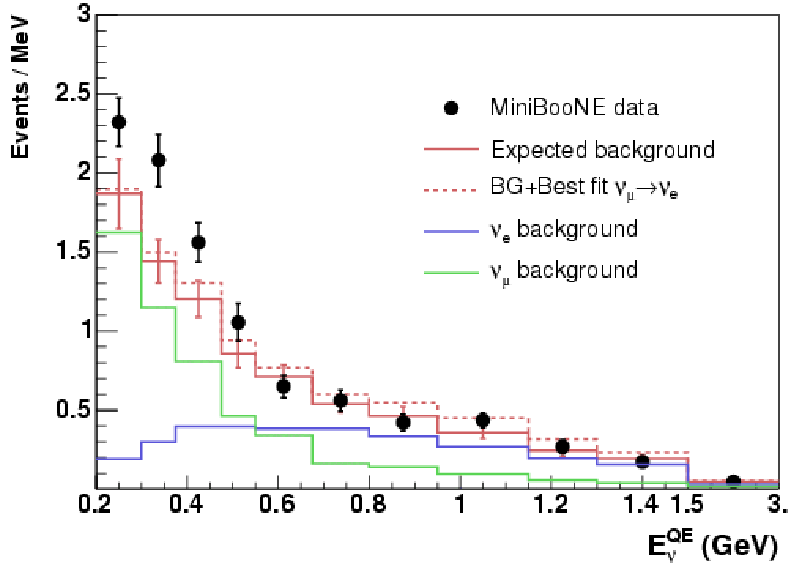




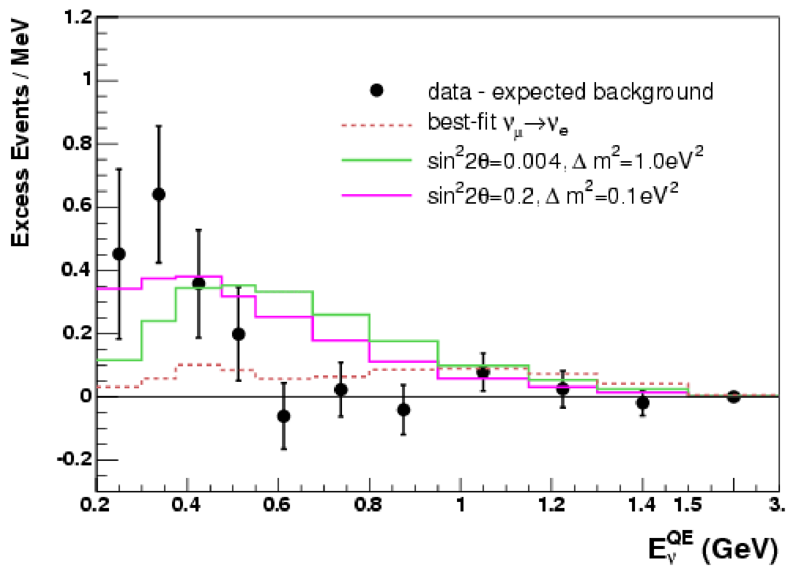


- Little impact on primary oscillation analysis!

Final Results: Extend 2ν fit to low E



	E_ν>475 MeV	E_ν>200 MeV
Null fit χ^2 (prob.):	9.1(91%)	22.0(28%)
Best fit χ^2 (prob.):	7.2(93%)	18.3(37%)



- Adding 3 bins to fit causes chi^2 to increase by 11 (expected 3)
- Can see the problem...the best 2ν fit that can be found does not describe the low E excess.

Final Results: Compare update stages

Event Sample	Original (April 07)	Updated Analysis	Add New Data	Add Dirt Cut
200 − 300 MeV				
Data	375	368	427	232
Background	283 ± 37	332.4 ± 38.9	386.0 ± 44.3	186.8 ± 26.0
Excess	92 ± 37	35.6 ± 38.9	41.0 ± 44.3	45.2 ± 26.0
Significance	2.5σ	0.9σ	0.9σ	1.7σ
300 − 475 MeV				
Data	369	364	428	312
Background	273 ± 26	282.9 ± 28.3	330.0 ± 31.8	228.3 ± 24.5
Excess	96 ± 26	81.1 ± 28.3	98.0 ± 31.8	83.7 ± 24.5
Significance	3.7σ	2.9σ	3.1σ	3.4σ
200 − 475 MeV				
Data	744	732	855	544
Background	556 ± 54	615.3 ± 58.0	716.1 ± 66.2	415.2 ± 43.4
Excess	188 ± 54	116.7 ± 58.0	138.9 ± 66.2	128.8 ± 43.4
Significance	3.5σ	2.0σ	2.1σ	3.0σ
475 − 1250 MeV				
Data	380	369	431	408
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Significance	0.6σ	0.4σ	0.5σ	0.6σ

FINAL

- Divided into 4 major rows based on energy range
- Columns separate analysis updates
  - Original
  - All update except new data and dirt cut
  - Add new data
  - Add new dirt

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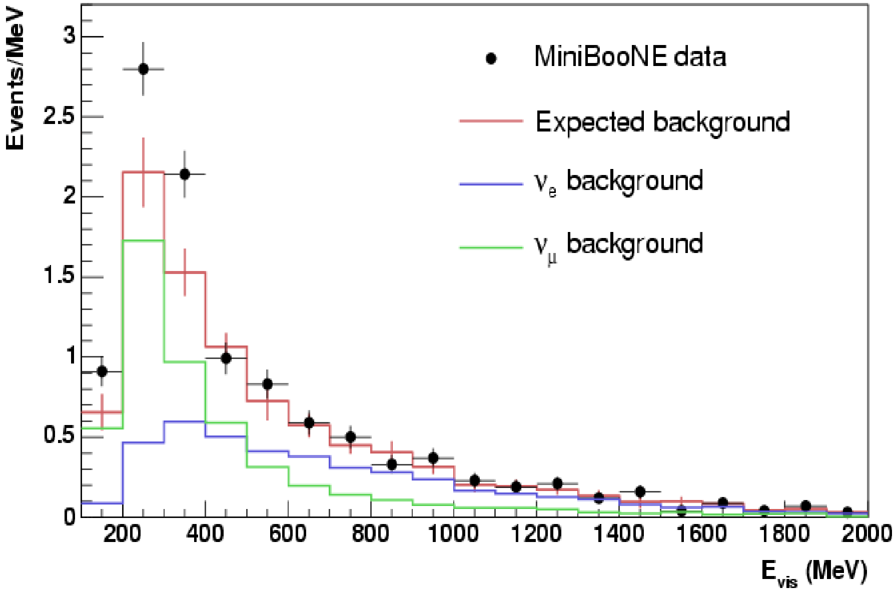
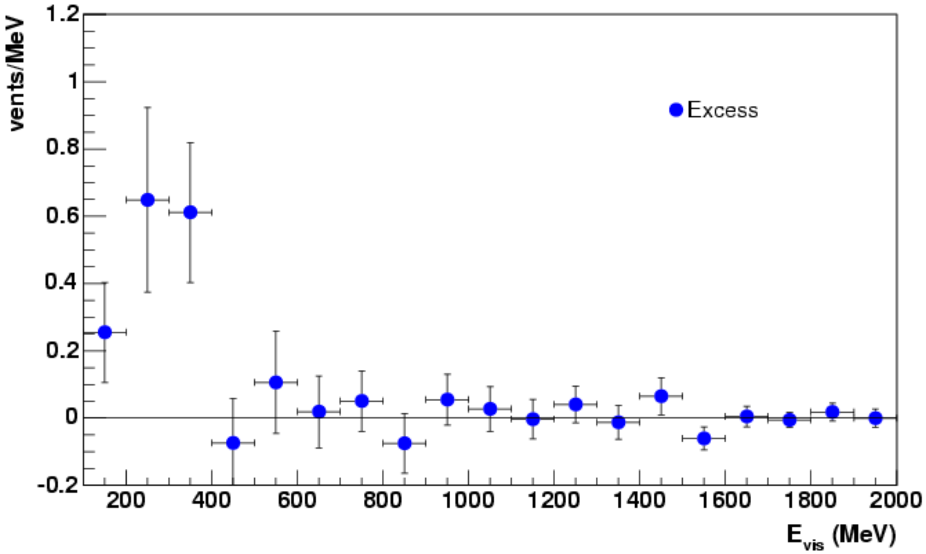
Final Results: Visible energy distribution

- Visible energy interesting to look at in case excess is not really due to ν_e CCQE
- Excess piles up below 400 MeV, analysis threshold set at 140 MeV Evis





$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

Antineutrinos in MiniBooNE

Antineutrinos in MiniBooNE

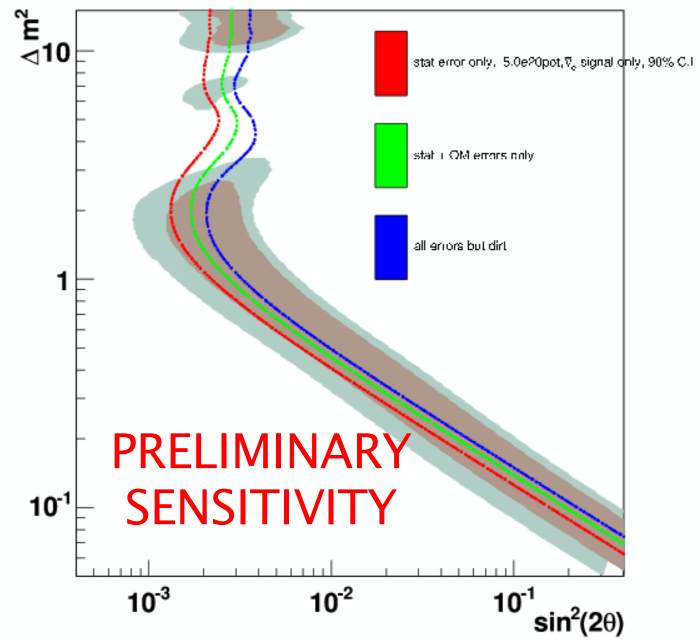
- Event rates after fiducial volume cuts:

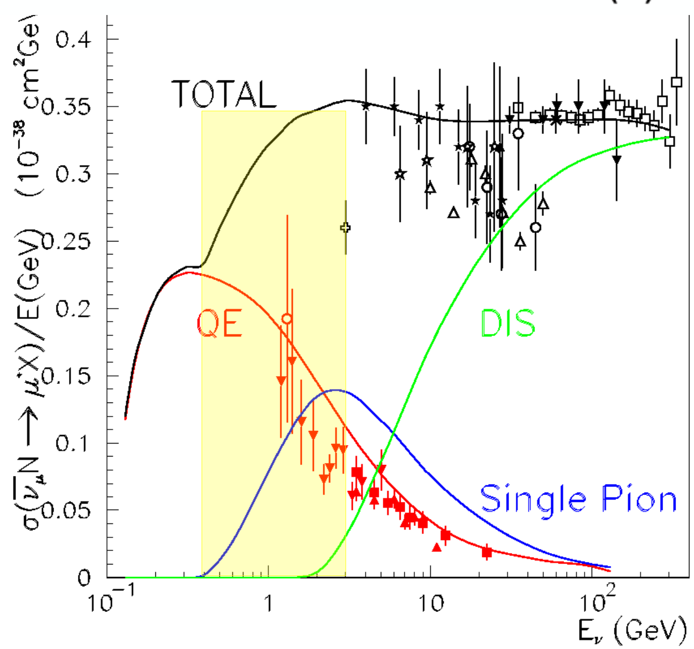
ν channel	events
all channels	810k
CC quasielastic	340k
NC elastic	150k
CC π^+	180k
CC π^0	30k
NC π^0	48k
NC $\pi^{+/-}$	27k
CC/NC DIS, multi-π	35k

6×10^{20} POT
ν mode

$\bar{\nu}$ channel	events
all channels	54k
CC quasielastic	24k
NC elastic	10k
CC π^-	8.9k
CC π^0	1.7k
NC π^0	4.9k
NC $\pi^{+/-}$	1.8k
CC/NC DIS, multi-π	1.9k

2×10^{20} POT
$\bar{\nu}$ mode





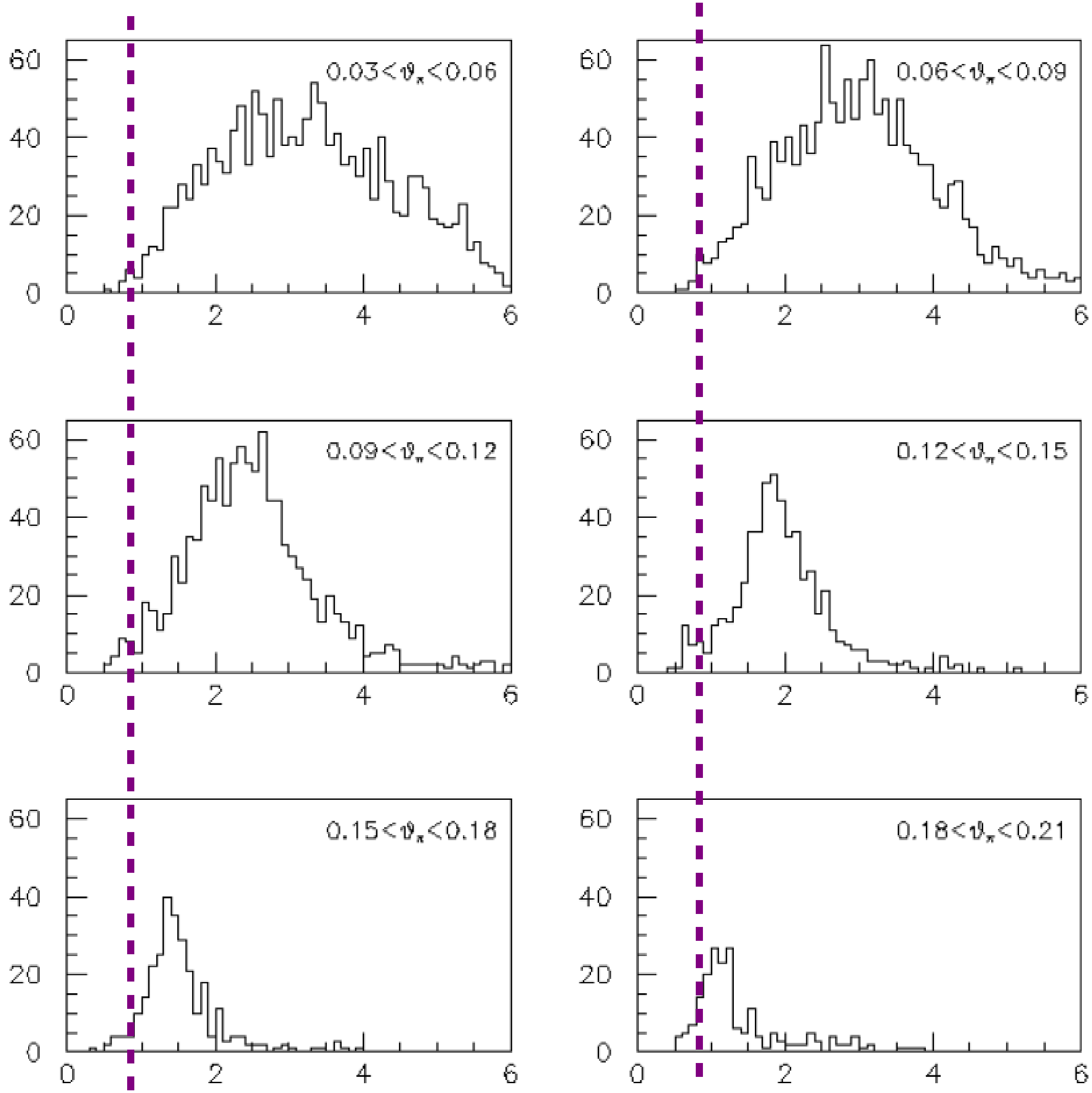
- Have collected 3.3E20 POT in antineutrino mode
  - Direct check of LSND result
  - Cross-sections measurements
  - Understanding low E excess

Conclusions and references

- Summary
  - A comprehensive review of all backgrounds and errors (with a particular emphasis at low E) has been completed
  - No change to the analysis above 475 MeV
  - The excess at low E energy is still >3.0σ significant, and remains a mystery
  - Next step: pulling together additional information from NuMI events and antineutrinos (still blind) into a global picture.
- For more info on MiniBooNE see
  - *Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon,* **PRL 100, 032310 (2008)**
  - *First Observation of Coherent π^0 Production in Neutrino Nucleus Interactions with En<2 GeV,* **Phys Lett B. 664, 41 (2008)**
  - *Compatibility of High Δm^2 ν_e and Anti-ν_e Neutrino Oscillations Searches,* **Phys. Rev D 78, 012007 (2008)**
  - *The Neutrino Flux Prediction at MiniBooNE,* **Accepted by PRD [arXiv:0806:1449]**
  - *The MiniBooNE Detector,* **Submitted to NIM A [arXiv:0806.4201]**
- Papers on the immediate horizon
  - NuMI events in MiniBooNE
  - BDT/TBL combination technique and result
  - Analyzing the low E events in MiniBooNE (this work)
  - CCpi+/CCQE ratio measurement
  - ν_μ disappearance in MiniBoone

Extra slides

Parent π kinematics -> make nue-like bkgs



Parent π kinematics -> make nue-like bkgs